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MAGNITUDE/YIELD VARIABILITY IN THE WESTERN UNITED STATES: ANALYSIS OF THE RULISON/GASBUGGY ANOMALY

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The investigations summarized in this report have centered on an attempt to develop a quantitative understanding of the Rulison/Gasbuggy m_b/yield anomaly. This effort has encompassed comparative studies of near-regional, regional and teleseismic data recorded from these two explosions, as well as theoretical simulation analyses of selected near-regional and teleseismic data

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20. Abstract (continued)

sets. Various hypotheses which have been proposed to explain the m_b anomaly, including differences in explosive source coupling, variations in upper mantle attenuation beneath the two test sites and tectonic release effects have been considered and critically evaluated. Analysis of the evidence provided by the near-regional, broadband seismic data recorded from these two explosions indicates that the m_b/yield anomaly is not due to differences in explosive source coupling. Moreover, the results of theoretical simulation analyses of teleseismic P wave spectra recorded from Gasbuggy and Rulison, together with the results of "reciprocal" experiments conducted using data recorded at these sites, provide strong evidence that no upper mantle attenuation bias sufficient to explain the observed m_b anomaly exists between these two test sites. ~~However,~~ evidence is presented which indicates that significant tectonic release occurred on Rulison, and it is demonstrated that the characteristics of this inferred tectonic release are quantitatively consistent with the observed m_b/yield anomaly.

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I. INTRODUCTION

1.1 WESTERN U.S. m_b/YIELD ANOMALIES

At the present time, the yields of underground nuclear explosions are estimated primarily on the basis of the observed teleseismic m_b values. That is, the magnitudes (or "corrected" magnitudes) determined from seismic data recorded from foreign explosions are compared with magnitude/yield relations determined from the large sample of Nevada Test Site (NTS) explosions to obtain estimates of the energy release. One of the difficulties associated with this approach is that it has been demonstrated empirically that systematic variations in magnitude can occur in the absence of any obvious change in explosion source characteristics. This is the "magnitude bias" problem which contributes significantly to our current uncertainty in estimating the yields of explosions at uncalibrated foreign test sites. An example of such an effect is provided by the Gasbuggy/Rulison explosions which were detonated only a few hundred kilometers apart in very similar sedimentary basins. The event locations are shown in Figure 1. Despite a similarity in near source environments, the observed Rulison m_b value has been estimated to be as much as 0.4 magnitude units lower than that which would have been expected on the basis of the observed Gasbuggy m_b value. This is illustrated in Figure 2 which shows a comparison of Gasbuggy (29 kt) and Rulison (40 kt) m_b values with the magnitude/yield relation determined from a statistical fit to a large sample of NTS explosions in wet tuff/rhyolite (T/R) emplacement media. The dashed lines on this figure denote the 95% bounds on the wet T/R data set, and it can be seen that the Rulison m_b/yield value falls outside these bounds. This is in contrast to the three U.S. granite observations (*i.e.*, Hard Hat, Shoal and Pile Driver) shown on this figure which cluster tightly about the wet T/R

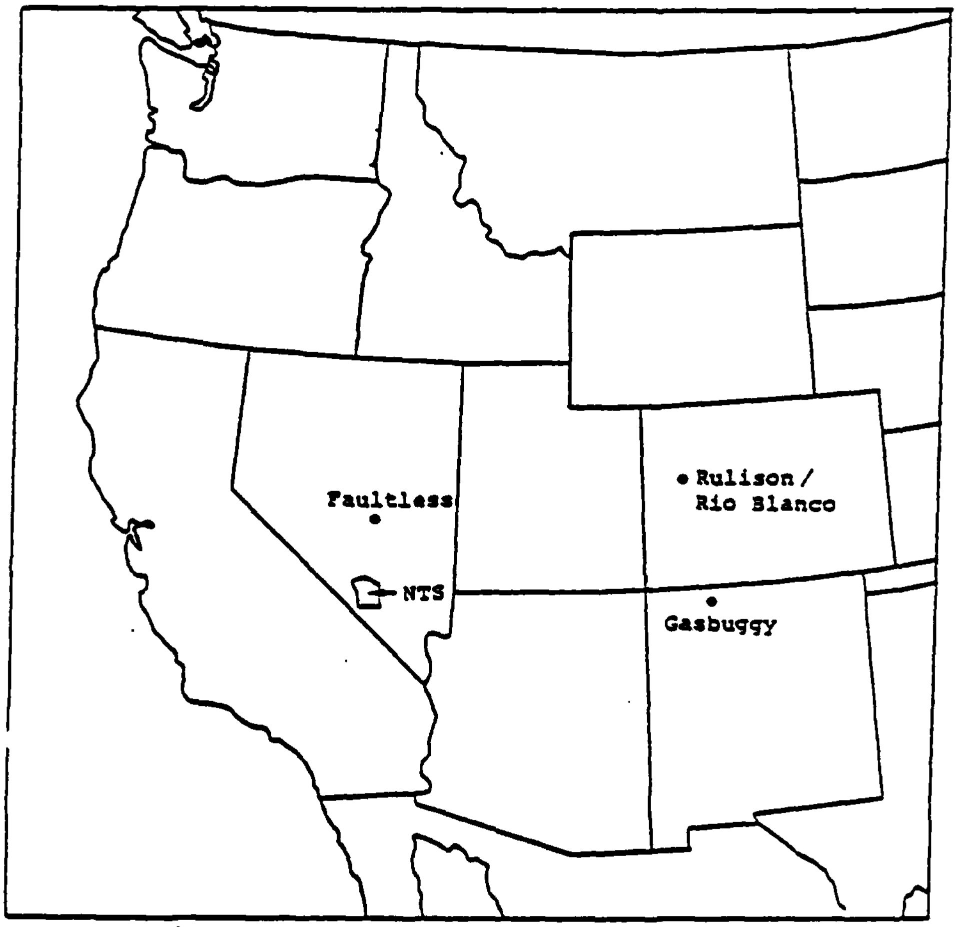

Figure 1. Event location map.

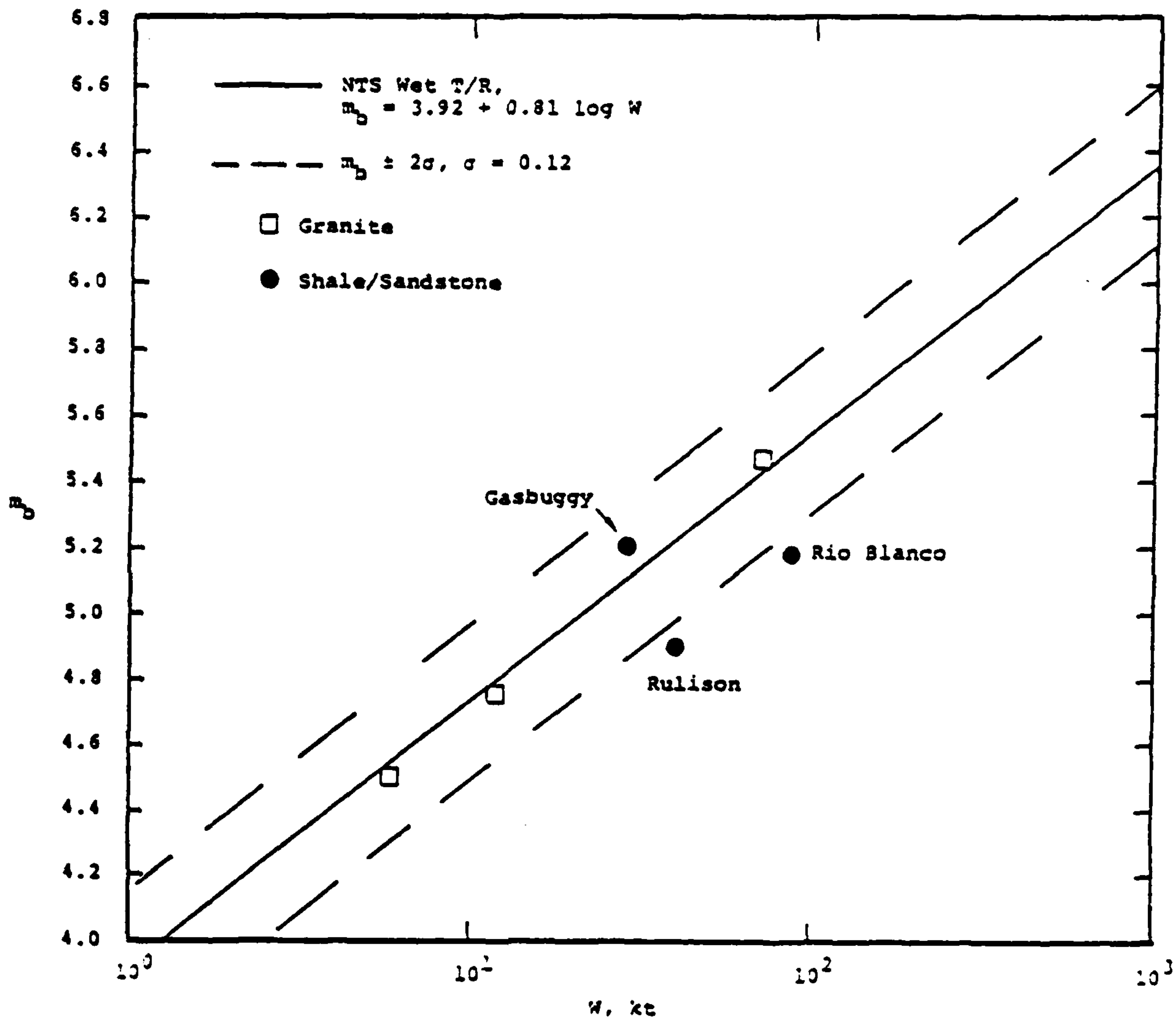

Figure 2. Comparison of m_b/yield data from selected Western U.S. explosions.

mean regression line. Thus, the observed Rulison m_b/yield value is significantly anomalous with respect to both the observed Gasbuggy value and average NTS experience. Moreover, it is clear that this is a regional, as opposed to a local source anomaly, in that the m_b/yield value for the Rio Blanco explosion, which was detonated about 50 km away from Rulison in the same sedimentary basin, also falls significantly below both Gasbuggy and average NTS experience. Another example is provided by the Faultless explosion which was detonated in a saturated tuff medium in Central Nevada, less than 150 km north of NTS (cf. Figure 1). Again, despite the similarity in source environments, the m_b/yield value for this explosion is observed to fall outside the 95% bounds on the NTS wet T/R sample.

Thus, there are well documented cases in which the magnitude/yield values of Western U.S. explosions show systematic deviations from average NTS experience. To date, no convincing, quantitative explanations have been provided for either the Rulison/Gasbuggy or Faultless/NTS anomalies which, respectively, define the lower and upper bounds of this observed variability. The objectives of the research summarized in this report have been to complete a comprehensive review and analysis of the various seismic data recorded from the Rulison and Gasbuggy events and to use these data to test and evaluate various hypotheses regarding the source of the m_b/yield anomaly associated with this pair of explosions.

1.2 SUMMARY OF EVIDENCE PROVIDED BY OBSERVED GASBUGGY/RULISON NEAR-REGIONAL SEISMIC DATA

In a previous report (Murphy, *et al.*, 1982), various types of seismic data recorded from the Gasbuggy and Rulison explosions were compared and evaluated in an attempt to identify potential sources of the magnitude/yield anomaly. In particular, the near-regional broadband data were analyzed in detail and used to compare the explosive seismic source

functions characteristic of the two events. For example, Figure 3 shows comparisons of the observed Rulison peak acceleration and spectral data with the predictions obtained by scaling the least-squares fits to the corresponding observed Gasbuggy data to the yield and depth of burial of Rulison using the scaling laws proposed by Mueller and Murphy (1971). It can be seen that the observed Rulison data agree remarkably well with the predictions based on Gasbuggy experience, indicating that the differences in the explosive seismic source functions between these two events are reasonably well understood. In contrast, it has been found that when the observed Gasbuggy m_b value is scaled to the yield and depth of Rulison using the same procedures used to scale the peak acceleration and spectral data, the predicted Rulison m_b value lies more than 0.3 magnitude units above the observed value. Thus, the evidence provided by the near-regional data strongly suggests that the m_b/yield anomaly is not due to differences in explosive source coupling.

The broadband, near-regional data recorded from Gasbuggy have also been modeled deterministically in an attempt to further constrain the seismic source functions (Murphy, *et al.*, 1982). The results of this analysis have confirmed that the individual explosive source functions, as well as their ratios, are consistent with the representation proposed by Mueller and Murphy (1971). That is, the main features of the observed Gasbuggy data can be explained using this selected source description together with a plane-layered propagation path model of the sedimentary basin in which Gasbuggy was detonated. For example, Figure 4 shows a comparison of the synthetic and average observed Gasbuggy particle velocity spectra at a range of 50 km. It can be seen that the synthetic spectrum, which was computed using Harvey's (1981) locked-mode, modal synthesis technique, agrees quite well with the observed data, which suggests that the nominal

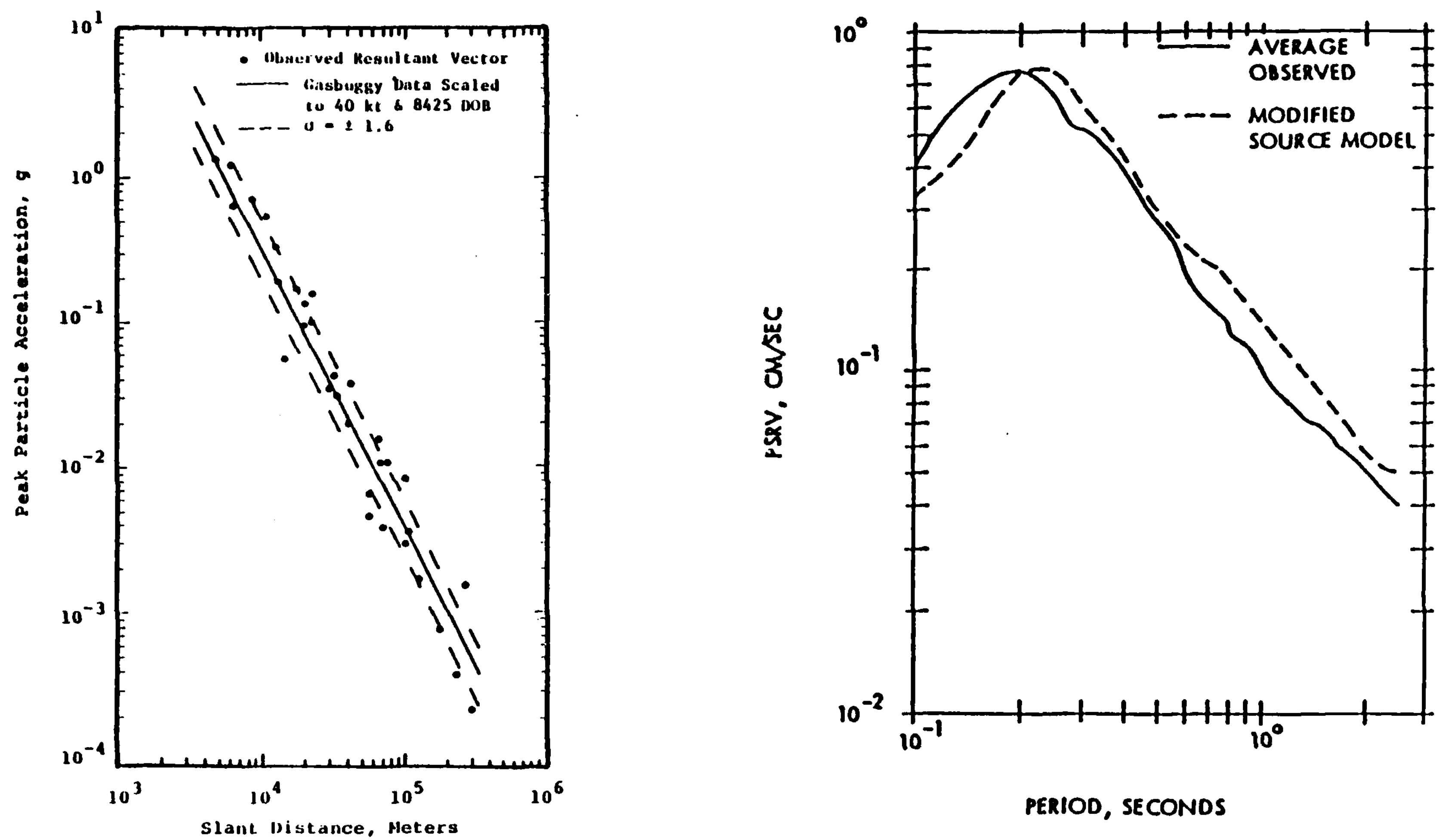

Figure 3. Comparison of observed Rulison peak acceleration data (left) and average observed ground motion spectrum at a range of 50 km (right) with predictions obtained by scaling average observed Gasbuggy data to the yield and depth of burial of Rulison.

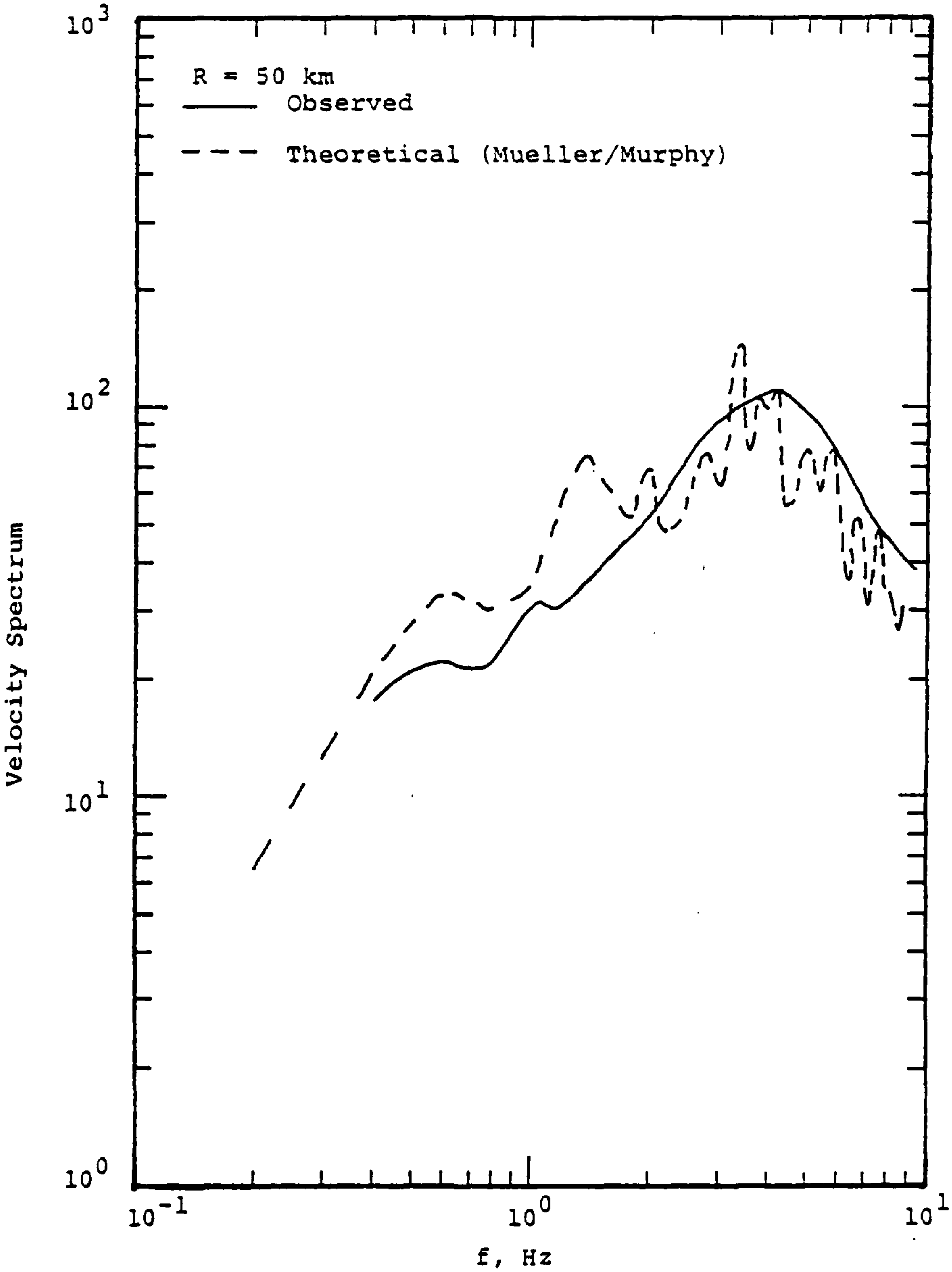

Figure 4. Comparison of synthetic and observed particle velocity spectra for Gasbuggy, R = 50 km.

Mueller/Murphy explosive seismic source function for Gasbuggy is a reasonable approximation for seismic modeling purposes. A corollary to this, which follows from the scaling results shown in Figure 3, is that the frequency dependence of the Rulison explosive seismic source function is also well represented by the Mueller/Murphy approximation.

In summary, the evidence provided by the near-regional seismic data appears to rule out variations in explosive source coupling as the cause of the Rulison/Gasbuggy m_b/yield anomaly. For this reason, the research effort described in this report has focused on the quantitative evaluation of the potential influence of other source and propagation path variables on the P waves observed at teleseismic distances from these two explosions.

1.3 REPORT ORGANIZATION

Section II of this report presents a systematic comparison and analysis of the teleseismic P wave data recorded at common stations from the Gasbuggy and Rulison explosions, with particular emphasis on their implications with respect to the hypothesis that the observed magnitude bias may be due to variations in upper mantle attenuation beneath the two test sites. This is followed in Section III by the detailed evaluation of an alternate hypothesis in which the observed m_b anomaly is attributed to the effects of a tectonic release which may have been triggered by the Rulison explosion. A summary and statement of conclusions are presented in Section IV.

II. COMPARISON AND ANALYSIS OF TELESEISMIC P WAVE DATA RECORDED FROM GASBUGGY AND RULISON

It was noted in a previous interim report (Murphy, *et al.*, 1982) that the most convincing case for the existence of a teleseismic m_b anomaly between Rulison and Gasbuggy can be made by direct comparisons of the waveforms recorded at common stations. Figure 5 shows such a comparison for the four WWSSN stations at which the signals from both events are of good enough quality to be digitized. It can be seen that the initial P waves at all four of these stations are clearly larger for Gasbuggy than for Rulison, in agreement with the differences in the published m_b values for these events and, contrary to what would be expected on the basis of their relative yields. Moreover, these differences are highly significant with respect to the normal magnitude/yield variability at these stations. This fact is illustrated in Figure 6 which compares the size of the Gasbuggy/Rulison m_b/yield anomaly at College, Alaska (COL) with the scatter bounds associated with a representative sample of NTS events recorded at this station. It seems clear from this figure that the observed anomaly can not be attributed to random variability.

Another feature of the waveforms of Figure 5 which was discussed in the previous interim report is the remarkable similarity of the recordings at COL and Arequipa, Peru (ARE), particularly for Gasbuggy which was recorded at high signal-to-noise ratios at both stations. Note that despite the large differences in epicentral distance (36° vs. 63°) and azimuth (332° vs. 141°), the Gasbuggy waveforms at these two stations are virtual overlays. This suggests that the propagation path effects to these two sites are very similar and, therefore, probably very simple. It follows that the prominent characteristics of these waveforms should primarily be a function of the seismic source function and source region

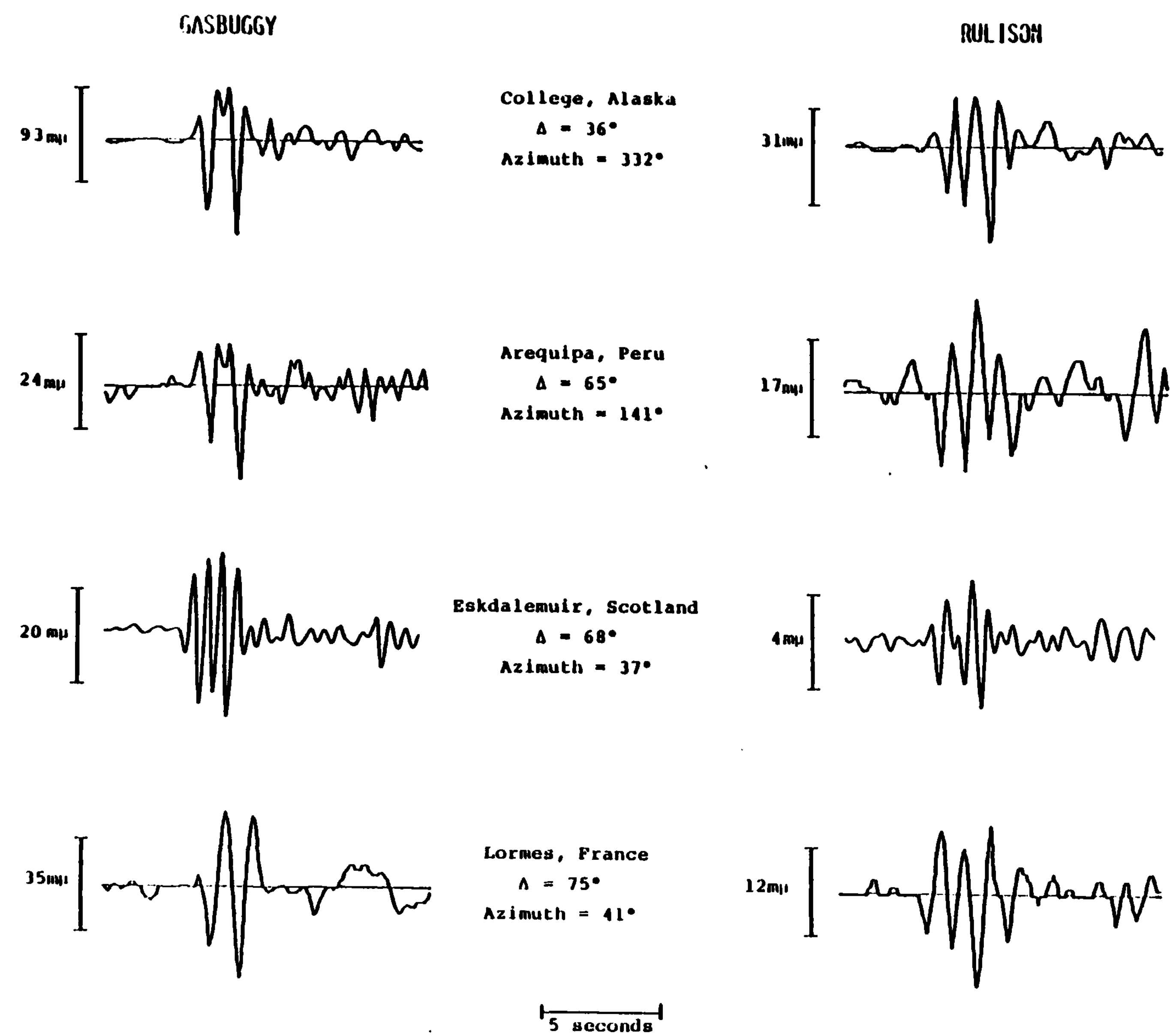

Figure 5. Comparison of Gasbuggy and Rulison short-period P waves recorded at four common WWSSN teleseismic stations.

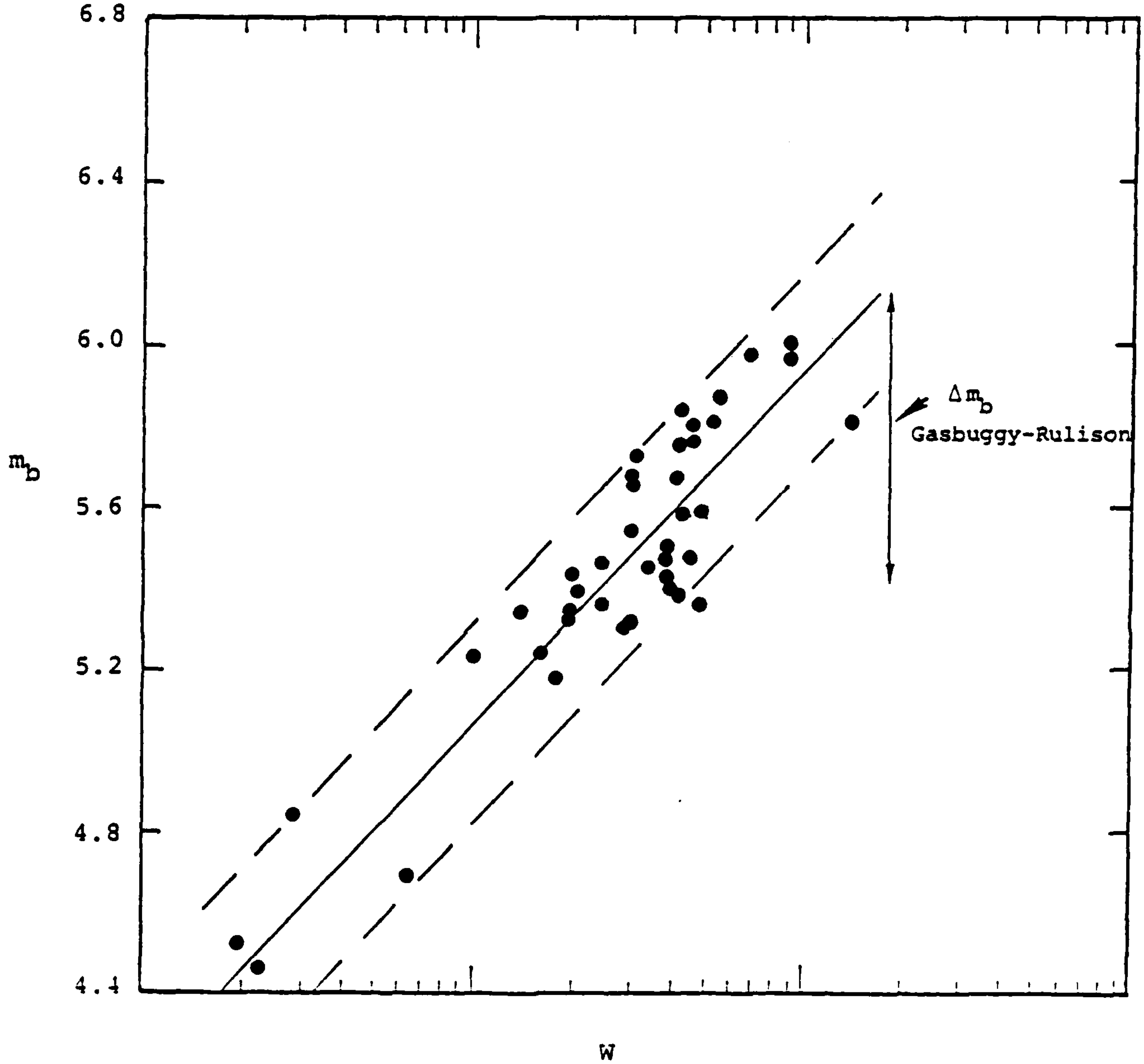

Figure 6. Comparison of Gasbuggy/Rulison m_b anomaly with distribution of NTS m_b/yield values at College, Alaska (COL).

crustal structure effects which are common to both. For these reasons, the teleseismic P wave synthesis studies were initiated with an analysis of the short-period Gasbuggy data recorded at these two sites.

The computational procedures which have been employed in the P wave synthesis studies have been described by Murphy, *et al.* (1982). For all the applications described in this report, the mantle transfer functions have been computed using velocity model PEMC (Dziewonski, *et al.*, 1977) and, in view of the simplicity of the P waves observed at stations COL and ARE, the receiver crustal structure at both these sites has been approximated using a simple, essentially transparent model. Figure 7, from Murphy, *et al.* (1982), shows the results of attempting to simulate the observed Gasbuggy P wave signal at COL through a linear superposition of the direct P and surface reflected pP phases induced by a Mueller/Murphy (1971) approximation to the explosion seismic source function. It can be seen that by assuming a standard t* linear attenuation model with a t* value of 0.5 seconds, the amplitude level and frequency content of the first cycle of the observed motion can be matched quite closely. However, it is clear that no linear combination of P and elastic pP can account for the second major downswing which occurs about 1.5 seconds after the first arrival. In fact, Murphy, *et al.* (1982) have shown that this large secondary arrival correlates very closely with the observed spall sequence on Gasbuggy. That is, a spall slapdown induced P wave with timing consistent with the observed Gasbuggy spall closure and an amplitude corresponding to a spall impulse of about one-half the Viecelli (1973) nominal value for a 30 kt explosion, when superposed with direct P, provides an excellent fit to the teleseismic observations. This is illustrated in Figure 8 which shows comparisons of the observed Gasbuggy P waves at COL and ARE with the synthetics obtained by superposing the direct and spall

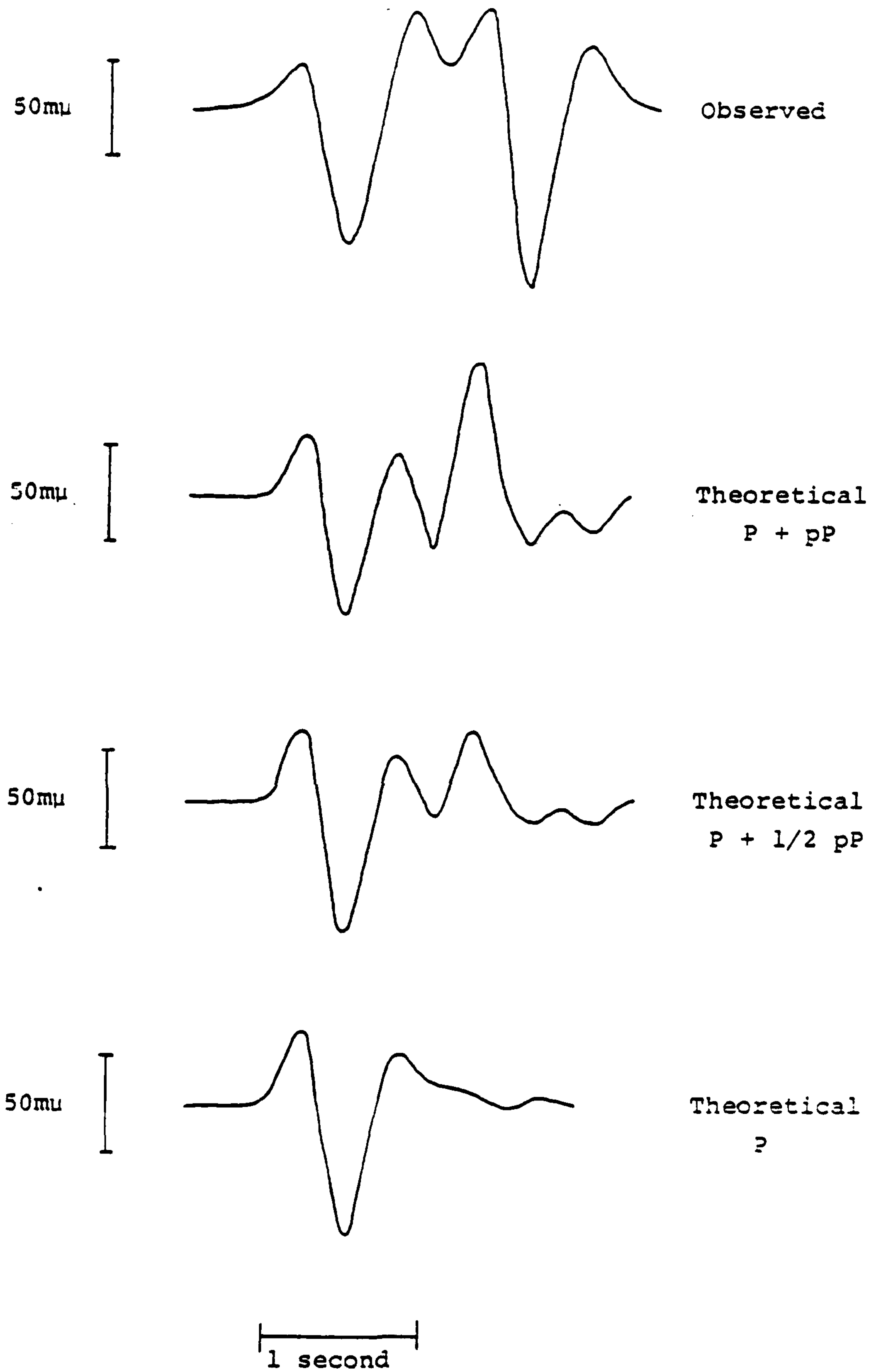

Figure 7. Comparison of observed and theoretical P waves for Gasbuggy at College, Alaska (COL), t* = 0.5 seconds.

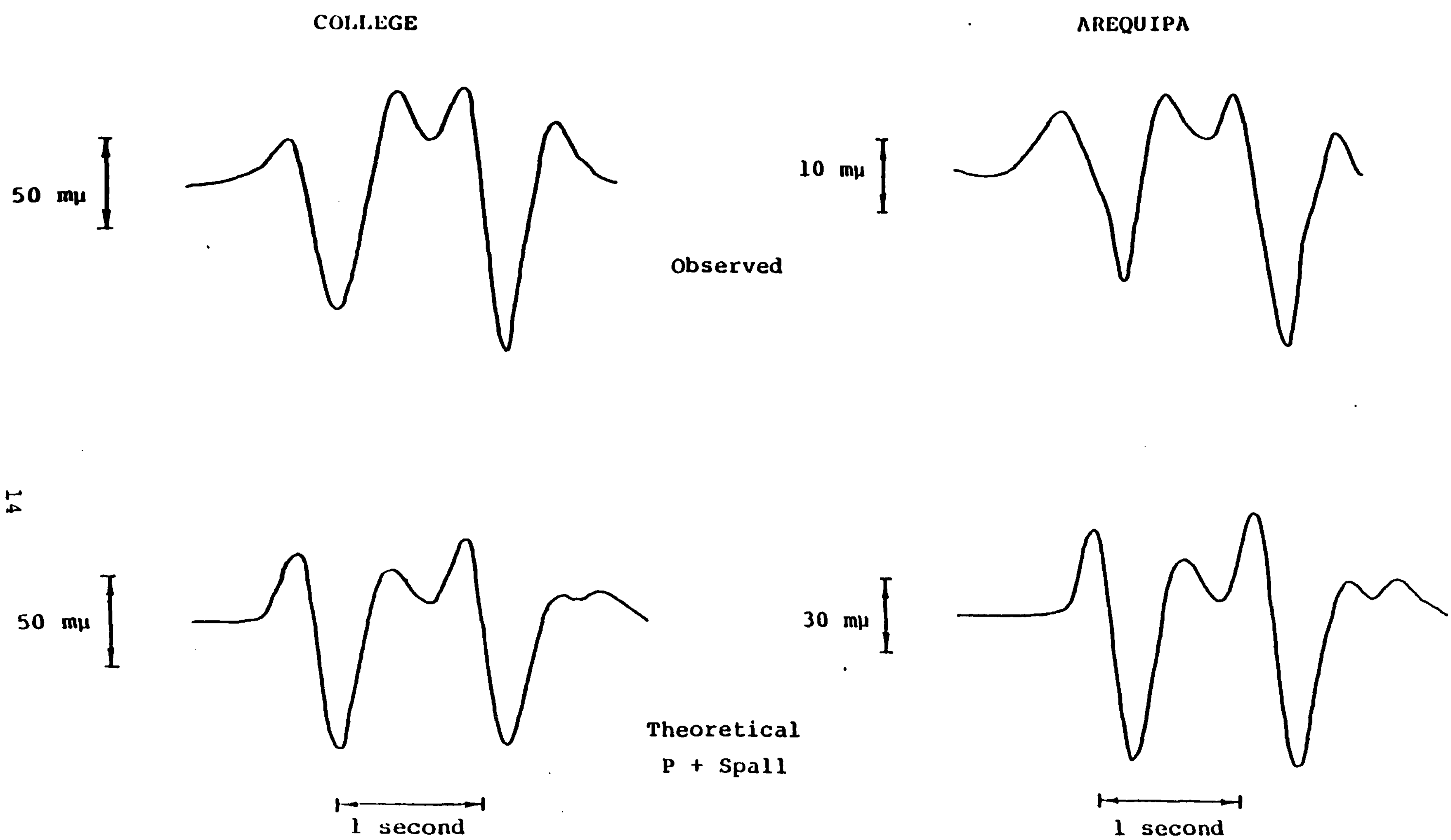

Figure 8. Comparison of observed Gasbuggy P waves at College, Alaska and Arequipa, Peru with the synthetic P waves computed by superposing direct P with P wave generated by Viecelli's spall model, t* = 0.5 seconds.

generated P waves. It can be seen that the complete P waveforms are matched quite closely by this model. The amplitude level at ARE is overestimated somewhat when the COL t* value of 0.5 seconds is assumed for that path, but it can be shown (Murphy, *et al.*, 1982) that the predicted and observed amplitude levels can be brought into closer agreement, without seriously compromising the waveform fit, by increasing the t* value for this path to about 0.7 seconds.

Given this initial success at modeling the Gasbuggy teleseismic P waves recorded at COL and ARE, an effort was initiated to model the corresponding Rulison P waves observed at these same two stations. The approximation to the Rulison crustal structure used in these simulation studies is shown in Figure 9. As with Gasbuggy, the simple Mueller/Murphy (1971) compressional point source was used as the initial source representation for Rulison. Figure 10 shows a comparison of the observed Rulison P waves at COL with the synthetics obtained by superposing the direct P and pP phases induced by this source. As with Gasbuggy, the observed Rulison P wave train is considerably more complex than these simple P plus pP synthetics. However, again, even the simple model can adequately reproduce the amplitude and frequency content of the initial cycle of the motion. In this case, however, a t* value of about 0.9 seconds is required, as compared to the t* value of about 0.5 seconds which was inferred from the Gasbuggy recording at this same station. The overall waveform fit can be improved in this case also by incorporating inferred spall closure effects similar to those invoked for Gasbuggy. Unfortunately, in the case of Rulison there are no free-field data which can be used to constrain the timing and amplitude of the spall generated P phases. However, by simply adjusting the observed Gasbuggy spall parameters to account for the greater depth and yield of Rulison, synthetic P waves are obtained which agree with the observed data nearly

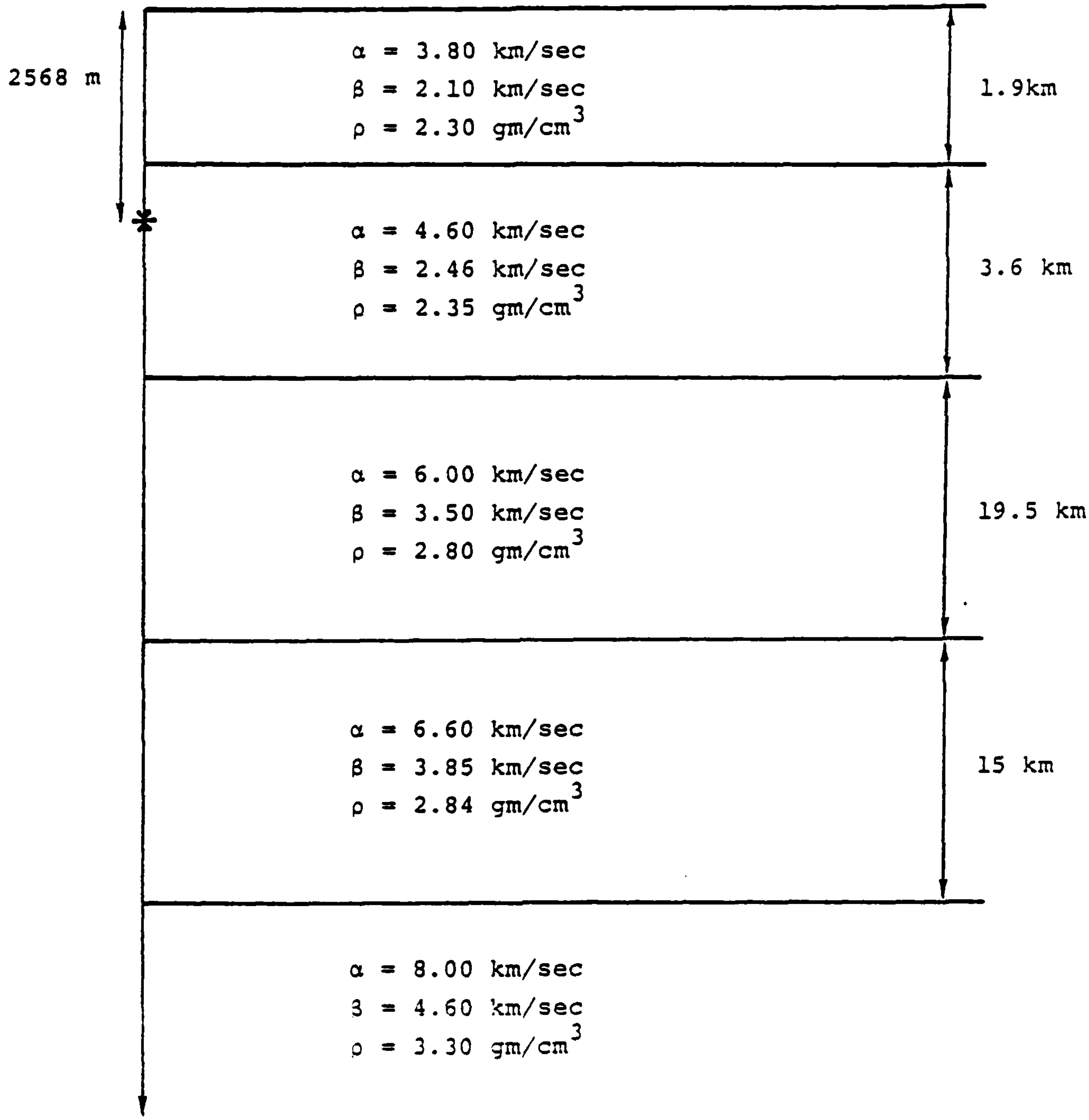

Figure 9. Rulison crustal model.

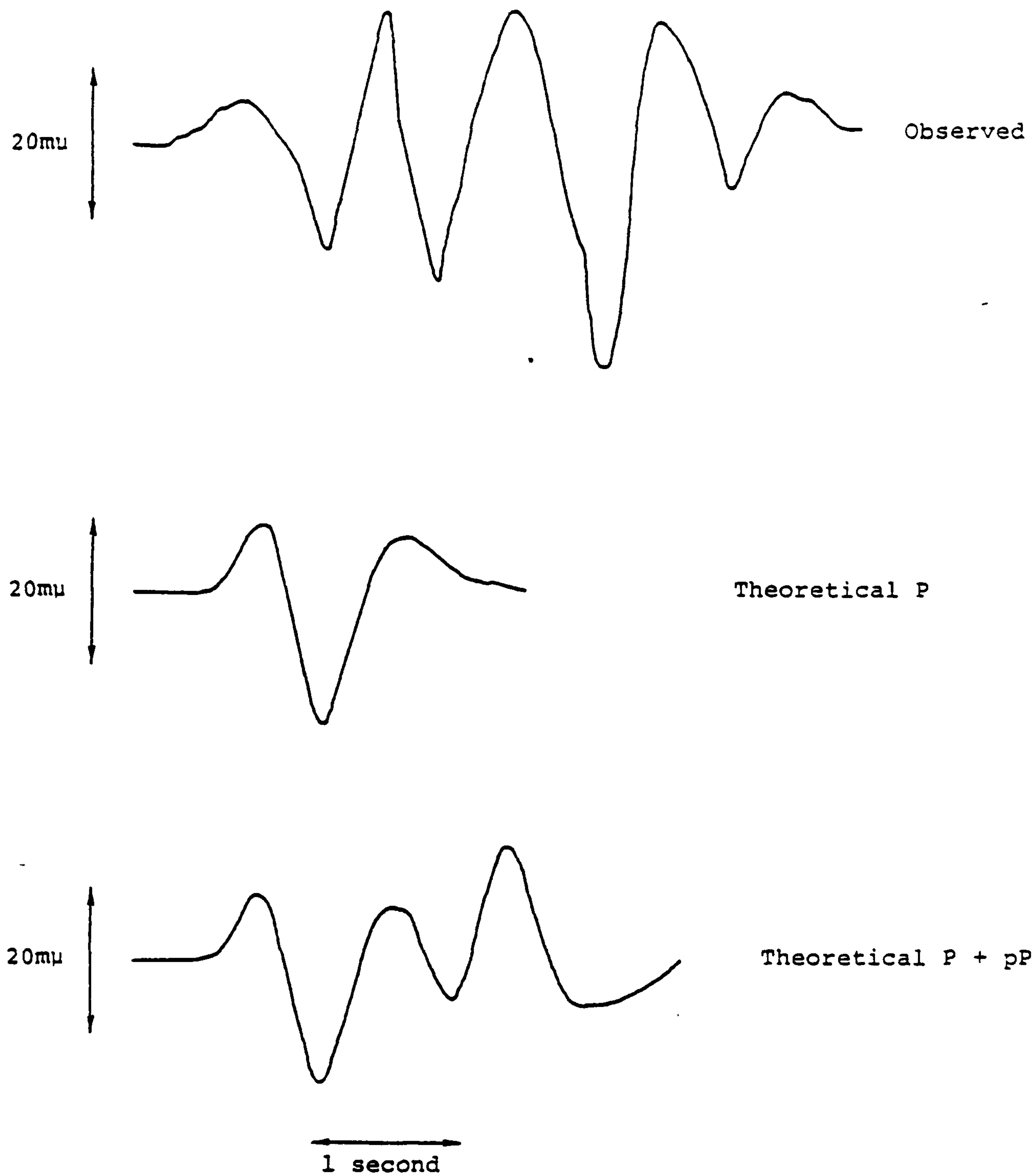

Figure 10. Comparison of observed and theoretical P waves for Rulison at College, Alaska (COL), $t^* = 0.9$.

as well as those for Gasbuggy. This is illustrated in Figure 11 which shows comparisons of the observed and synthetic Rulison P waves at COL and ARE. As was noted previously, a t* value of 0.9 seconds is consistent with the observed COL amplitude level, while a t* value of about 1.0 can account for the observed ARE amplitude level. That is, a Δt* of approximately 0.3 to 0.4 seconds between the Rulison and Gasbuggy paths to COL and ARE can explain the observed amplitude anomalies at these sites.

The hypothesis that the Rulison/Gasbuggy m_b/yield anomaly might be due to differences in upper mantle attenuation beneath the two sites has been proposed previously (*e.g.*, Marshall, *et al.*, 1979). However, the Δt* value inferred from the above analysis is very large, and would appear to be inconsistent with the generally similar geophysical setting of the two sites. Moreover, Der, *et al.* (1981) have recorded teleseismic P waves simultaneously at the Gasbuggy and Rulison/Rio Blanco sites and have found no evidence of significant differences in the upper mantle attenuation beneath the two sites. The results of their analysis are summarized in Figure 12 which shows histograms of the differences in m_b (Δm_b), t* (Δt*) and dominant period (ΔT) inferred from a large sample of earthquake data recorded at the two locations. It can be seen that these results do not provide any indication of a consistent bias between these two sites. It can, of course, be argued that these results are not definitive in that the measurement of earthquake generated teleseismic P wave data on the surface at the two sites is not rigorously reciprocal to the measurement of teleseismic P waves produced by buried explosions at these same sites. In order to investigate this point in more detail, a synthetic experiment was conducted in which an explosive source was placed at a depth of 10 km in the COL crustal model (Murphy, *et al.*, 1982) and teleseismic P wave spectra were synthesized for observation points at the

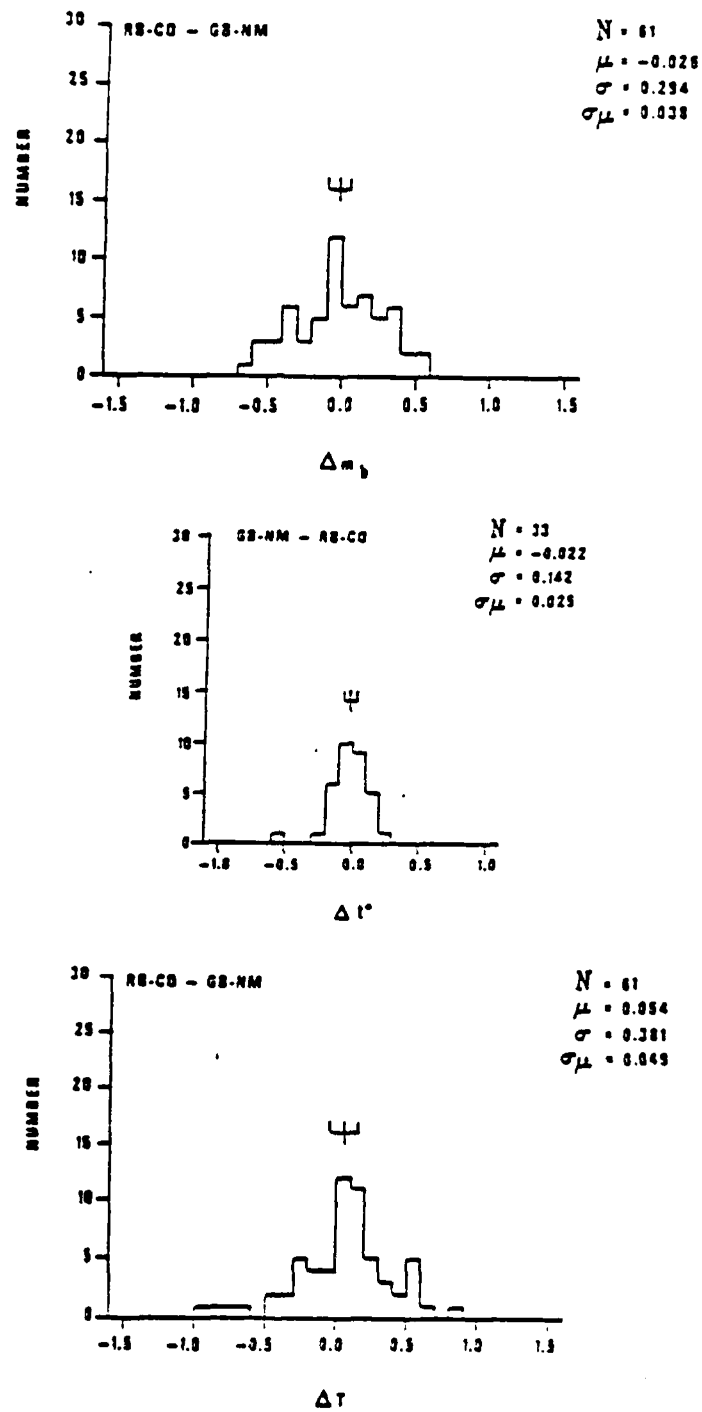

Figure 12. Histograms of observed differences in m_b (Δm_b), t* (Δt*) and dominant period (ΔT) inferred from teleseismic earthquake data recorded at the Gasbuggy (GB-NM) and Rio Blanco (RB-CO) sites (Der, *et al.*, 1981).

surface of the Gasbuggy and Rulison crustal models, assuming $t^* = 0.5$ seconds for the path to Gasbuggy and $t^* = 0.9$ seconds for the path to Rulison. The synthetic spectral ratio, Gasbuggy/Rulison, is shown as a solid line in Figure 13 where it is compared with the theoretical spectral ratios predicted to account for differences in t^* alone. It can be seen that, while the solid line is somewhat oscillatory due to the differences in assumed receiver crustal structures, it clearly indicates a significant difference in t^* which would be easy to detect in the measured data. Thus, the "reciprocal" data of Der, *et al.* (1981) are inconsistent with differences in t^* of the size needed to explain the observed amplitude anomalies at COL and ARE.

A more direct test can be provided by comparing the Gasbuggy and Rulison P wave spectra at common observation stations. As a first step in this analysis, synthetic and observed P wave spectra for Gasbuggy and Rulison were compared for station COL. Figure 14 shows the comparison of the synthetic P wave spectrum corresponding to the time domain waveform of Figure 8 with the spectrum computed from the first 3.2 seconds of the observed Gasbuggy P wave at COL. It can be seen that for frequencies below about 4 Hz, where the observed signal-to-noise ratio is greater than 2, the synthetic spectrum fits the observed spectrum very closely. More specifically, the t^* value of 0.5 seconds, which was adopted to match the time domain amplitude level, is consistent with the observed spectral shape. The corresponding comparison between the synthetic and observed Rulison P wave spectra at COL is shown in Figure 15. The dotted line in this figure is the synthetic P wave spectrum computed assuming the t^* value of 0.9 seconds which was required to match the observed Rulison time domain amplitude level. In this case, the observed spectral shape (solid line) is clearly inconsistent with the proposed value of t^*. In fact, the Rulison synthetic P wave

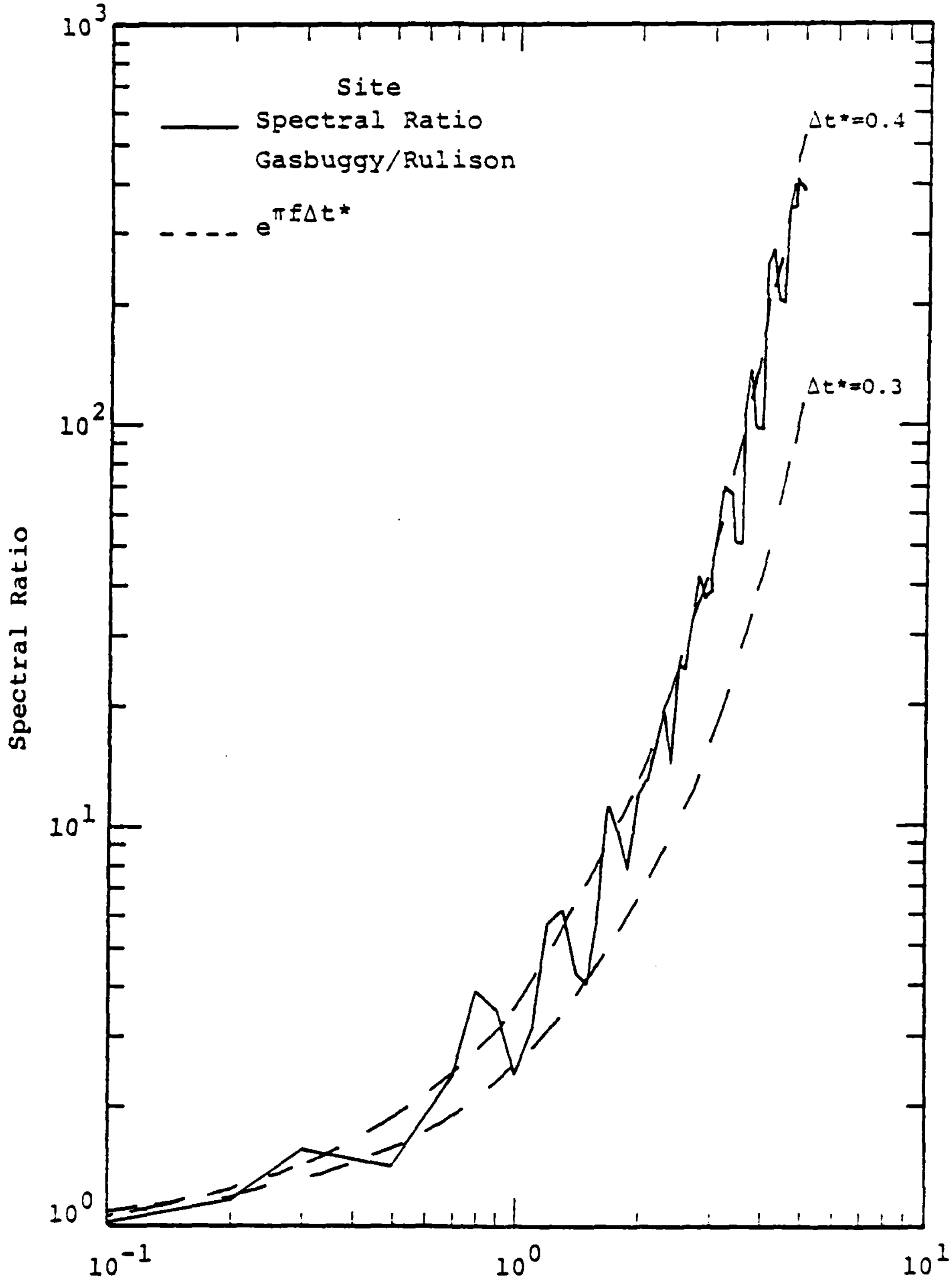

Figure 13. Ratio of theoretical spectra computed for observation points at the Rulison and Gasbuggy sites for a hypothetical Alaskan event assuming $\Delta t^* = 0.4$ seconds.

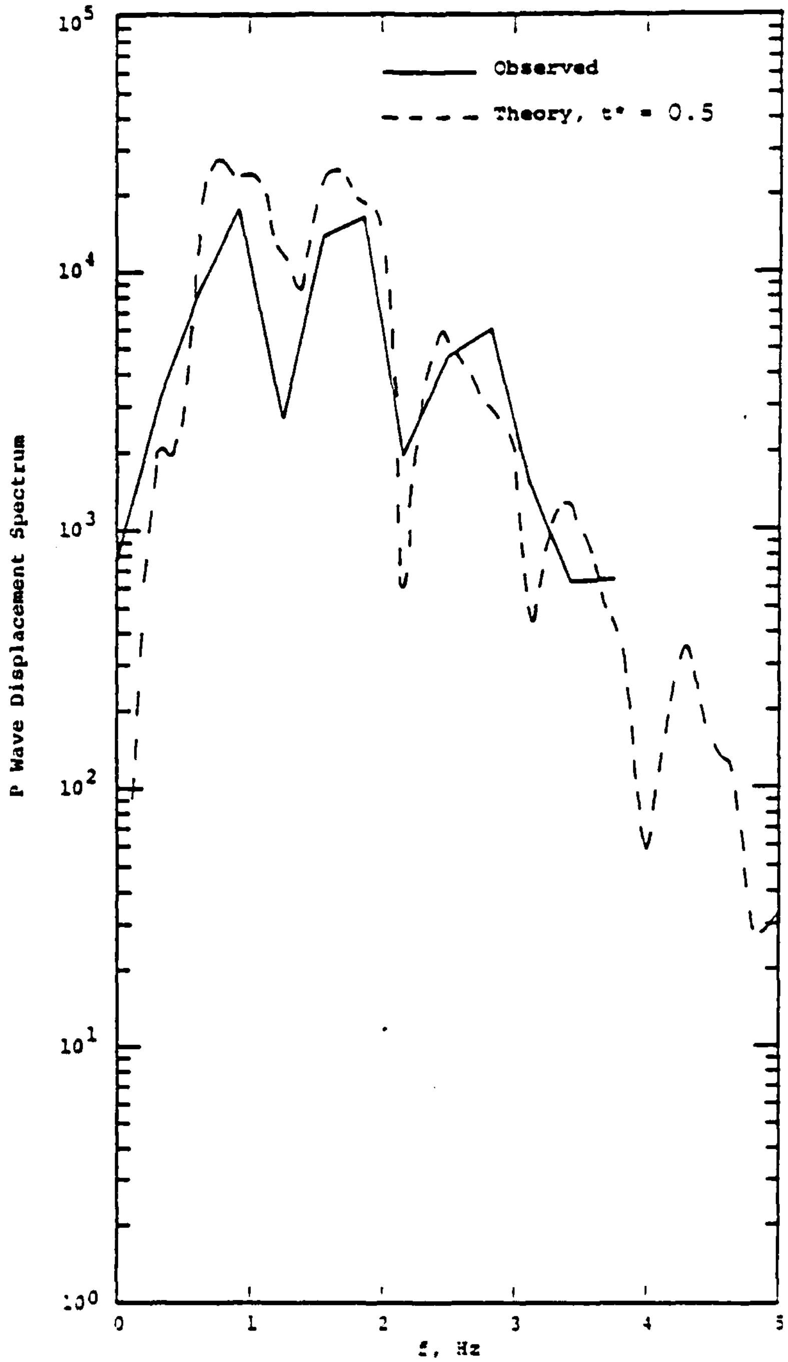

Figure 14. Comparison of theoretical and observed P wave displacement spectra for Gasbuggy at College, Alaska.

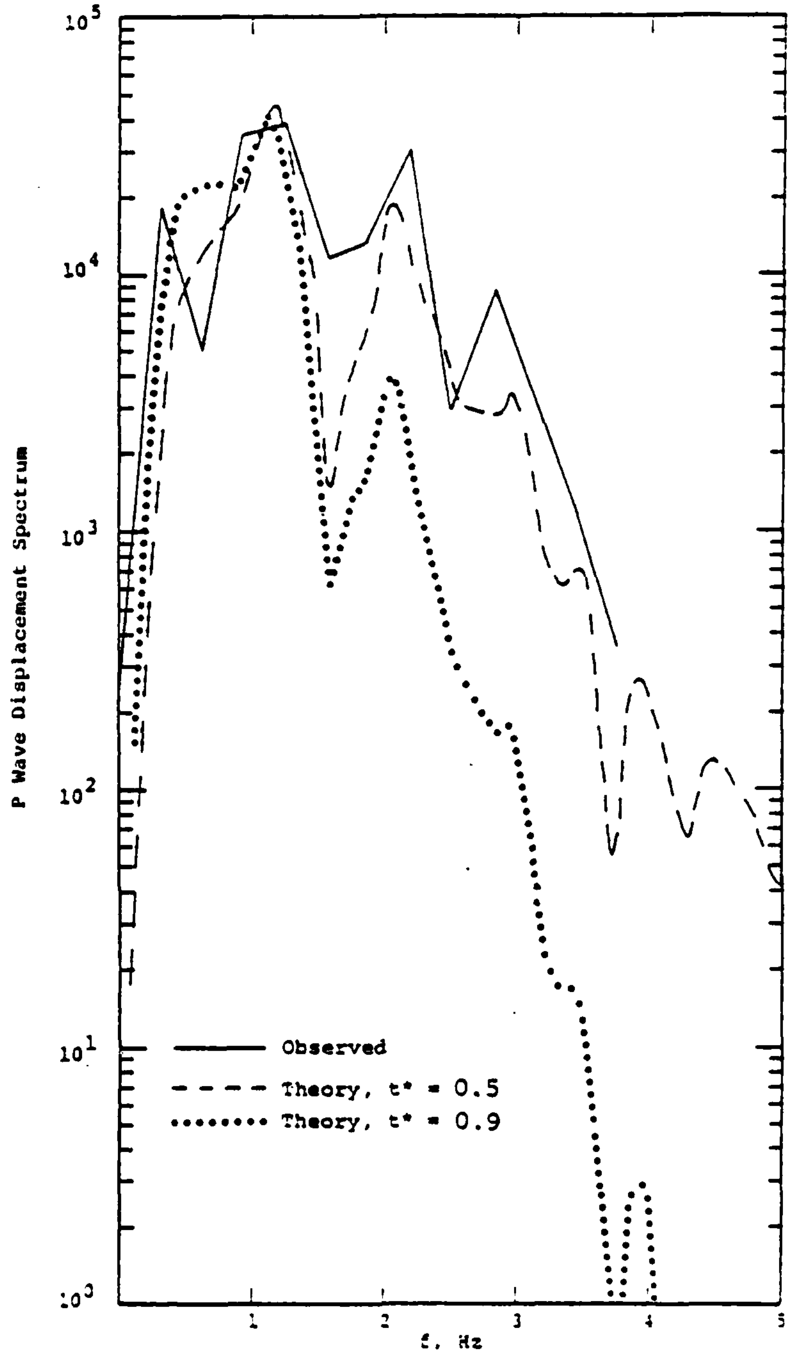

Figure 15. Comparison of theoretical and observed P wave displacement spectra for Rulison at College, Alaska.

spectrum, computed assuming the Gasbuggy t* value of 0.5 seconds and normalized to the observed spectral amplitude level at 1 Hz, provides a much better fit to the observed spectral shape. Thus, the COL spectral data are not consistent with the hypothesis that the m_b/yield anomaly is related to differences in upper mantle attenuation beneath the Gasbuggy and Rulison sites. A corollary to this is that, at least in this case, the "reciprocal" experiment data analyzed by Der, *et al.* (1981) provided an estimate of attenuation bias between the two sites which is consistent with the explosion teleseismic P wave observations.

Additional data bearing on this issue have been recorded from Gasbuggy and Rulison at a number of LRSM stations, most of which are located in the regional distance range. No attempt has been made to model these complex observations in any detail, but spectral ratios have been computed between the two events on a station by station basis. Figure 16 shows the theoretical spectral ratios (Rulison/Gasbuggy) that would be expected assuming Mueller/Murphy representations of the two seismic source functions and various values for the difference in t* between the two propagation paths (*i.e.*, $\Delta t^* = 0, 0.2, 0.4$ seconds). The observed Rulison/Gasbuggy P wave spectral ratios computed from the data recorded at the LRSM stations NPNT ($\Delta \approx 39°$), PGBC ($\Delta \approx 19°$) and RKON ($\Delta \approx 16°$) are shown in Figure 17. It can be seen that although these observed spectral ratios are all more complex than the theoretical ratios of Figure 16, they show no tendency to decrease with increasing frequency. In fact, with reference to Figure 16, the observed spectral ratios appear to be generally consistent with the theoretical prediction for $\Delta t^* = 0$ and are clearly inconsistent with Δt^* values even as large as 0.2 seconds.

In summary, the amplitude differences between the Gasbuggy and Rulison teleseismic P waves recorded at WWSSN stations COL and ARE can be attributed to upper mantle attenuation differences between the two test sites only if Δt^* values

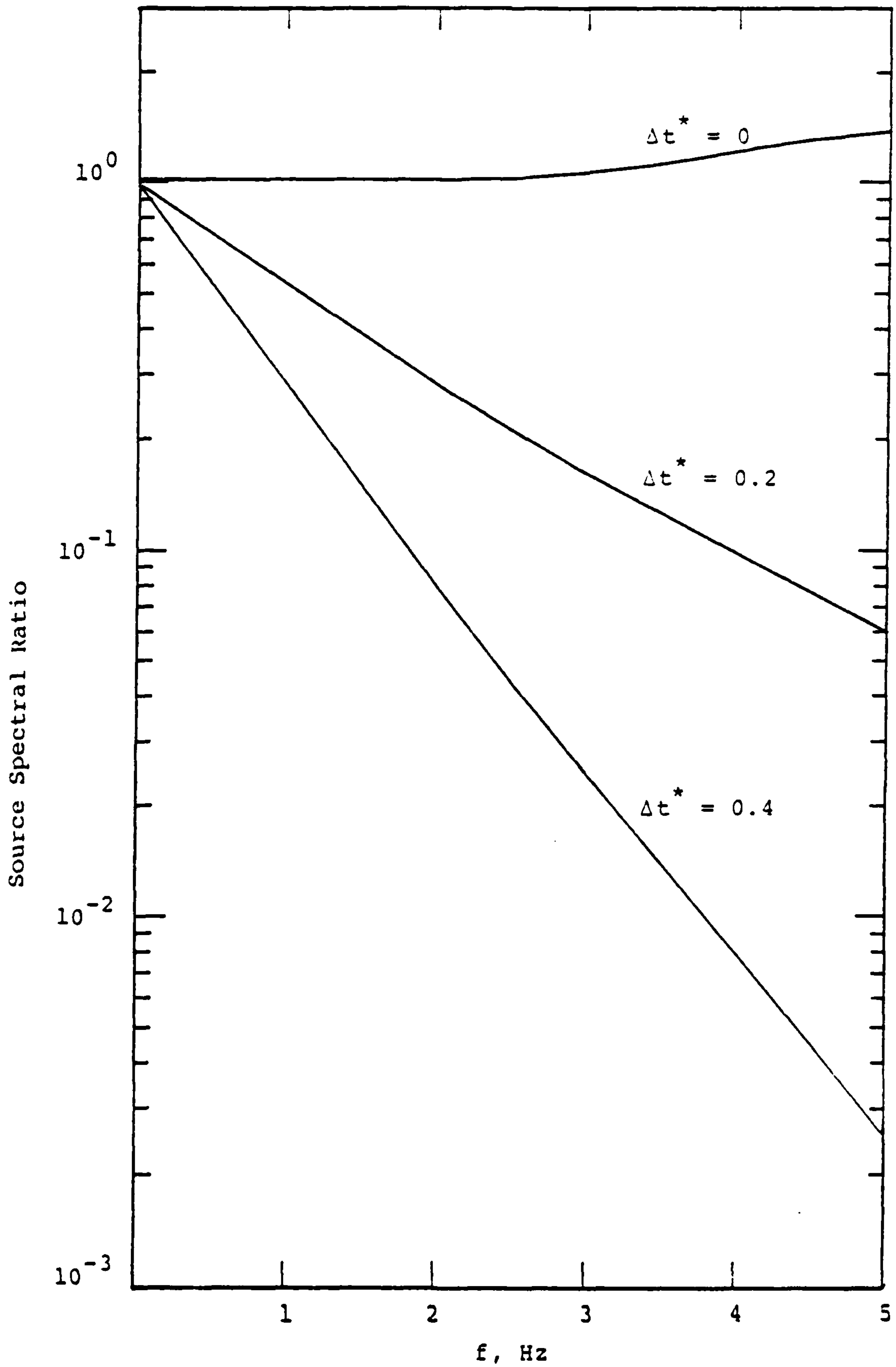

Figure 16. Theoretical Rulison/Gasbuggy P wave spectral ratios computed assuming a range of Δt^* values.

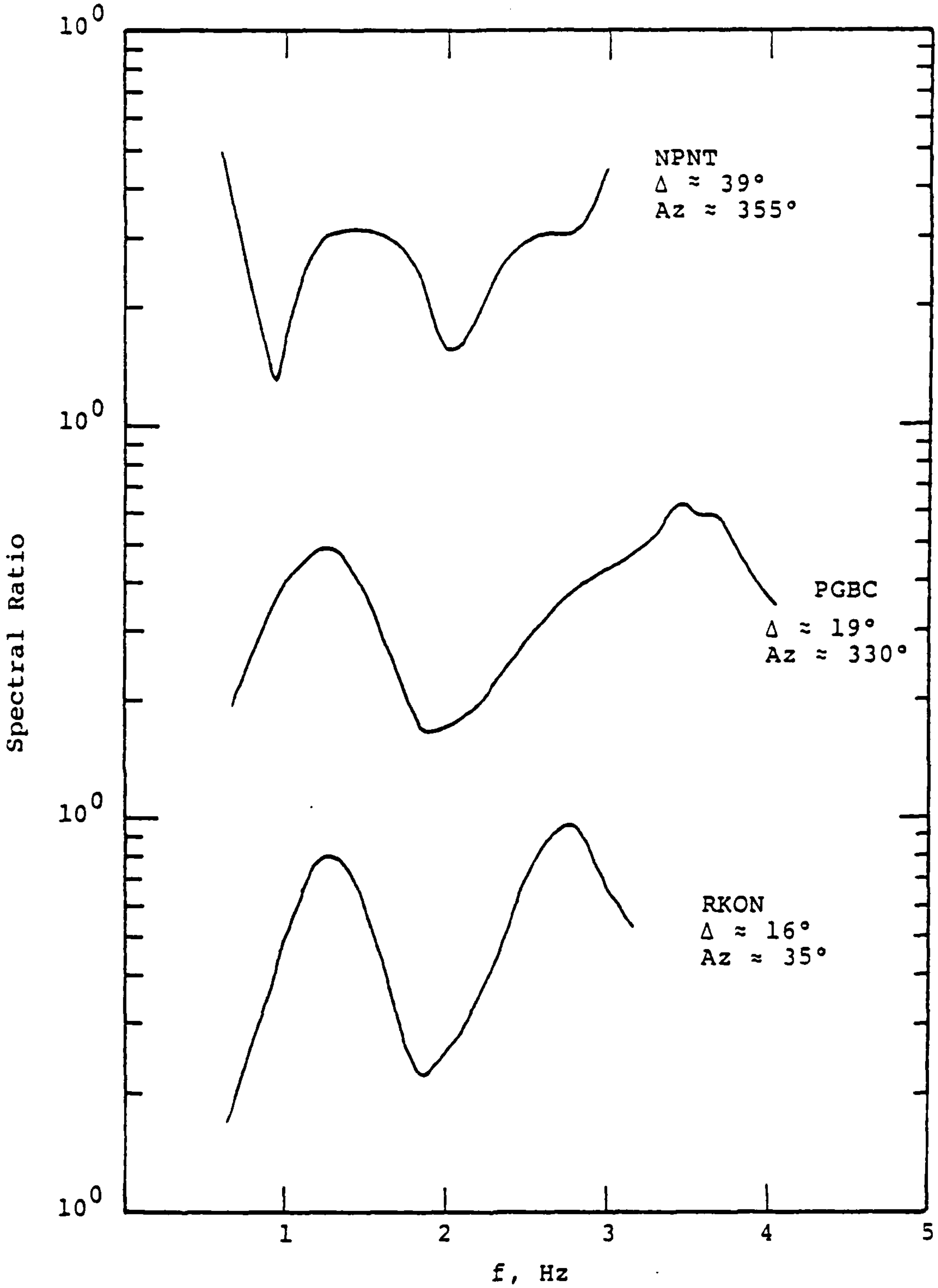

Figure 17. Observed Rulison/Gasbuggy P wave spectral ratios at LRSM stations NPNT, PGBC and RKON.

on the order of 0.3 to 0.4 seconds can be confirmed. However, theoretical simulation analyses of the P wave spectra recorded at COL, LRSM P wave spectral ratios and the "reciprocal" experiment results of Der, *et al.* (1981) all provide strong evidence that no such large attenuation bias exists between these two test sites. In fact, the available data are best described under the assumption that the attenuation bias (*i.e.*, Δt^*) between the Gasbuggy and Rulison sites is effectively zero. Thus, other potential sources of the m_b/yield anomaly need to be considered and evaluated.

III. AN ASSESSMENT OF EVIDENCE FOR TECTONIC RELEASE EFFECTS ON RULISON

The various lines of evidence presented in the preceding sections appear to rule out the possibilities that the Rulison/Gasbuggy m_b/yield anomaly can be explained either by differences in explosive source coupling or by variations in upper mantle attenuation beneath the two test sites. Given these results, an alternate hypothesis which must be considered is that tectonic release effects are biasing the observed m_b values. In this regard, it is interesting to note that although the measured Gasbuggy seismic data provide no clear evidence of tectonic contamination, it has long been known that there are a number of aspects of the observed Rulison data which do not appear to be consistent with a purely explosive source. Thus, for example, the initial CGS report on Rulison in the Seismological Notes (BSSA, April, 1970) states that "preliminary evaluation seems to indicate surface wave enrichment greater than would be expected from an explosive source." More specifically, significant long-period Love waves were observed from Rulison at a number of stations. One such observation is presented in Figure 18 which shows the three long-period components of motion measured from Rulison at the Canadian station FFC in Manitoba ($\Delta \approx 16°$). This station is located approximately due north from Rulison and, consequently, the E/W component is oriented nearly transverse to the surface wave direction of propagation. It can be seen that there is evidence of a significant long-period Love wave on this component which arrives prior to the arrival of the Rayleigh wave on the vertical and radial (*i.e.*, N/S) components of motion. Yacoub (1981) has recently completed an analysis of a large sample of long-period Rayleigh wave data measured from Rulison and has concluded that these data are also consistent with the hypothesis that significant tectonic

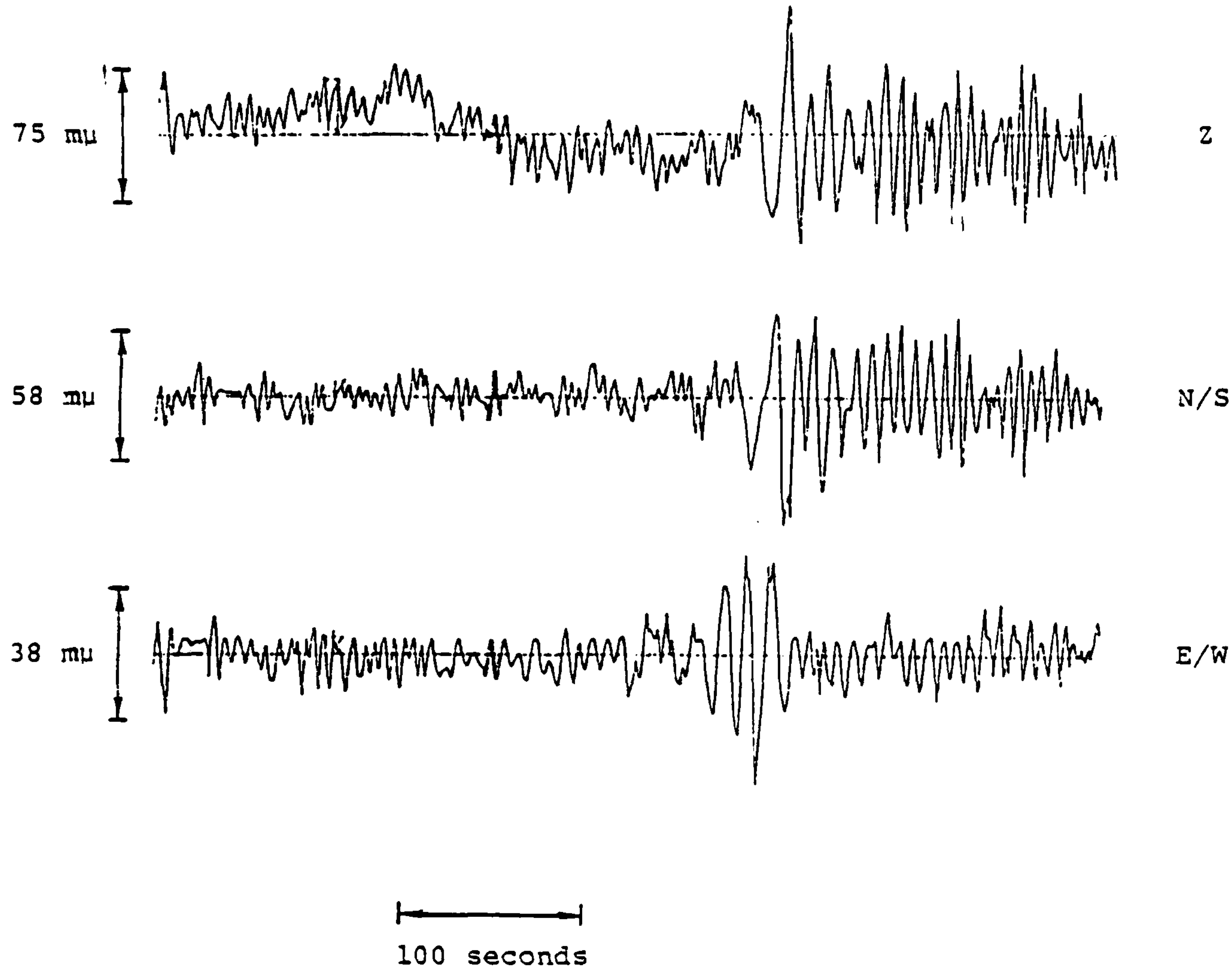

Figure 18. Long period components of motion measured from Rulison at the Canadian station FFC in Manitoba ($\Delta \approx 16°$).

release occurred on Rulison. The near-regional broadband data also provide some strong evidence of tectonic release. Figure 19 shows the three orthogonal components of particle velocity measured from Rulison at a station located about 23 km southwest of the detonation point, near Debeque, Colorado. It can be seen that there is a remarkably strong and coherent SH arrival on the transverse component which is larger than any arrival on either the radial or vertical components of motion. Although some transverse motion is nearly always observed at these distances from underground explosions, a discrete SH arrival of this amplitude must be regarded as highly anomalous, particularly since it has been identified on the recordings from a number of different Rulison near-regional stations (Environmental Research Corporation, 1970). Thus, there is strong evidence that significant tectonic release occurred on Rulison. The primary question that remains to be addressed concerns the issue of whether the characteristics of this tectonic release are consistent with the observed m_b anomaly, as well as with the variety of other seismic data recorded from this event.

The influence of tectonic release on teleseismic P waves from explosions has generally been dismissed in the past on the grounds that the tectonic stress drop required to significantly influence the short-period P waves appears to be implausibly large (cf. Bache, 1976). In fact, this argument is quite persuasive for tectonic release equivalent to strike-slip faulting on a vertical plane. Figure 20 shows the teleseismic body wave and surface wave radiation patterns corresponding to such a focal mechanism (Stevens, 1982). In this and subsequent examples shown in this section, the physical mechanism of the tectonic release has been assumed to be the sudden creation of a spherical cavity (*i.e.*, region in which material strength suddenly vanishes) in a uniformly prestressed medium (Archambeau, 1972; Stevens,

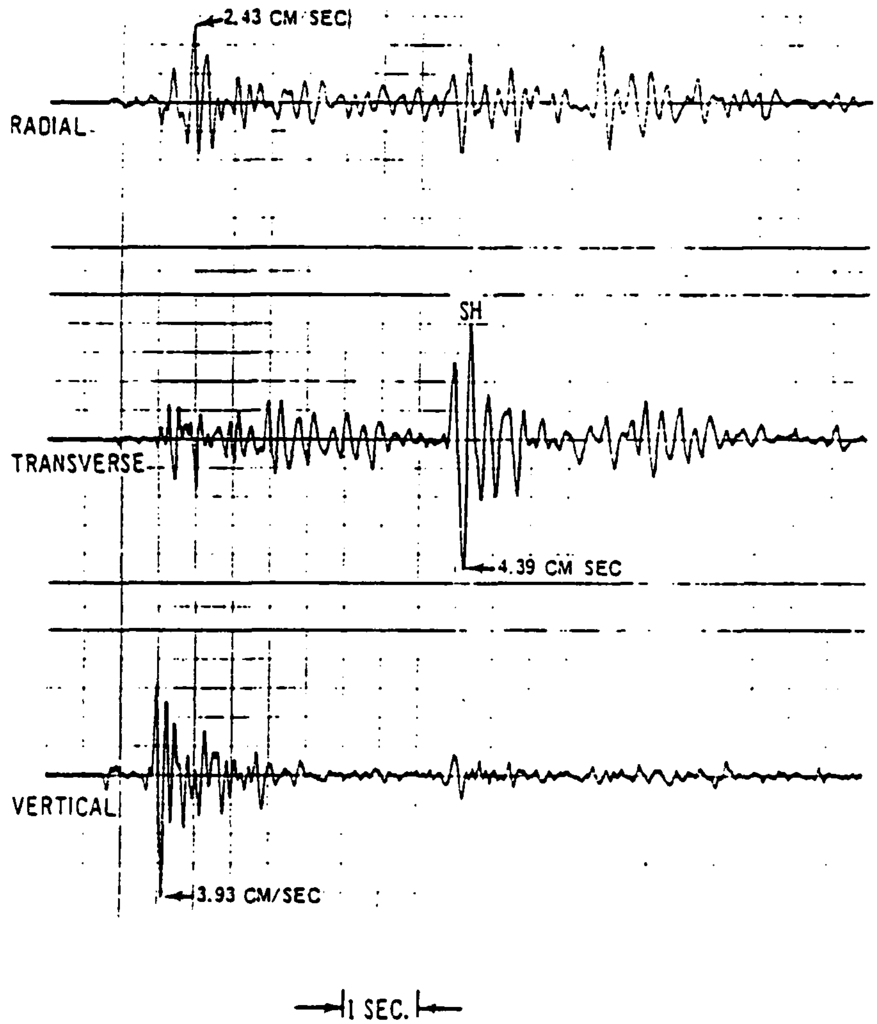

Figure 19. Broadband particle velocity seismograms measured from Rulison at Debeque, Colorado, Δ = 23 km.

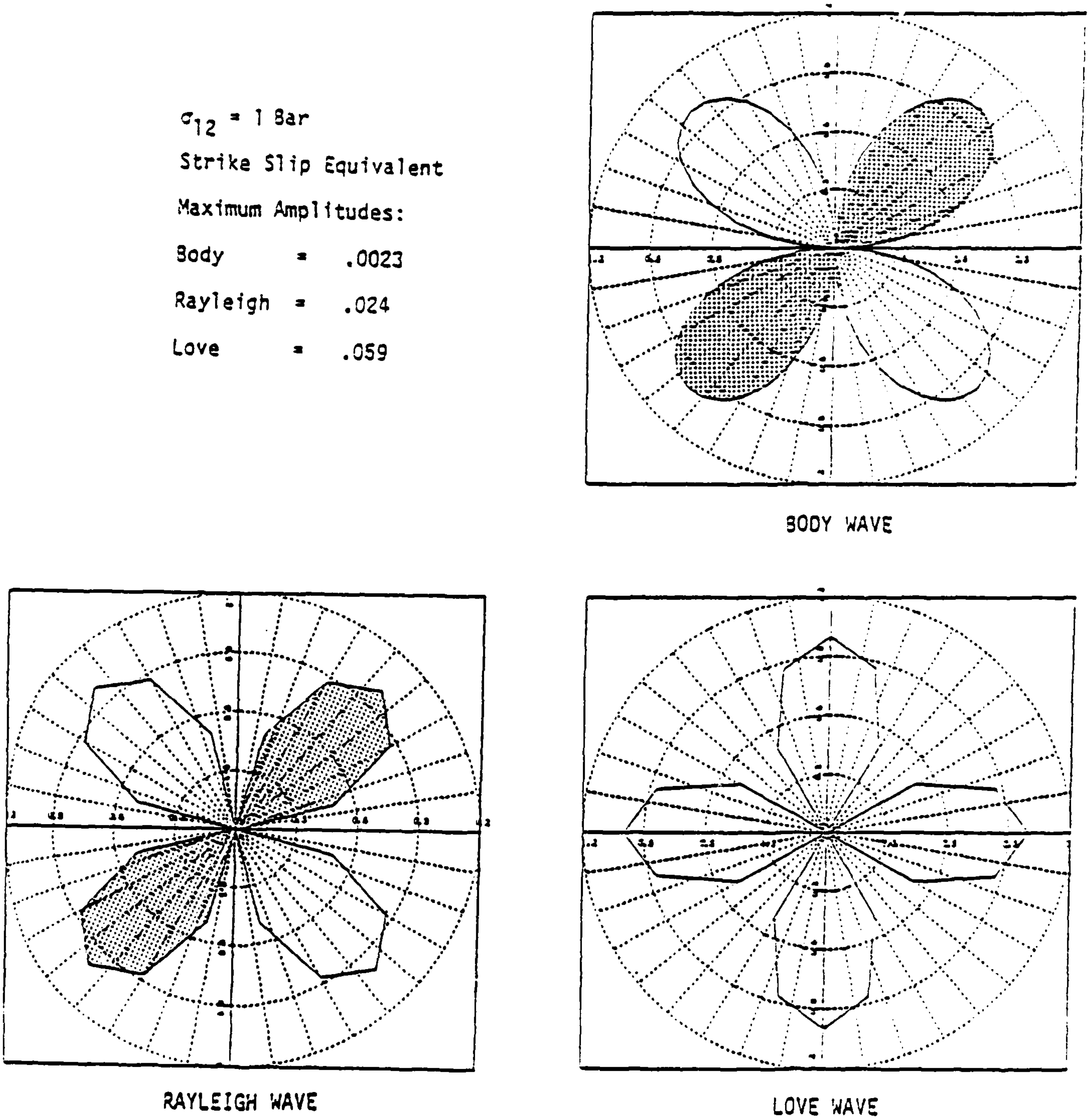

Figure 20. Theoretical radiation patterns for body and surface waves for tectonic release in a uniform prestress field equivalent to vertical strike slip faulting. Shaded areas indicate polarity opposite to the explosion. Body waves are calculated at 1 Hz and have a 28° takeoff angle. Surface wave amplitudes are computed at 20 second period. (Stevens, 1982).

1980), and the radius of this spherical cavity has been taken to be equal to the elastic radius of the explosion which induced the tectonic release. There are several features of the strike-slip tectonic release model of Figure 20 which tend to minimize its effect on m_b. The first is that the teleseismic P wave radiation pattern consists of four alternating lobes of compressions and dilatations. Thus, for a well distributed network of stations, the effect on m_b (and also M_s) will average out to zero. The second feature is that this focal mechanism generates body waves much less efficiently than it does surface waves. This can be seen by comparing the predicted maximum amplitude values listed on Figure 20. These values are normalized to the corresponding body and surface wave maximum amplitudes expected from the explosion source alone (in this case, Pile Driver) and correspond to a reference stress drop level of 1 bar. Thus, for the Pile Driver source, a tectonic stress drop of 435 bars is required to produce teleseismic body waves as large as those produced by the explosion. In contrast to this, a stress drop of only about 40 bars is required to produce tectonic Rayleigh waves (20 second period) as large as those produced by the explosion. It follows that vertical strike-slip tectonic release with stress drop large enough to significantly influence the teleseismic explosion P waves would be accompanied by tectonic Rayleigh and Love waves larger than any which have been reported to date from an explosion source (*i.e.*, an F factor of 3 or more).

For other focal mechanisms, however, the potential effects of tectonic release on m_b are not that easy to dismiss. For example, Figure 21 shows the body and surface wave radiation patterns for a 45 degree thrust fault (Stevens, 1982). In this case, the teleseismic P wave radiation pattern is nearly circular and the P waves from tectonic release can be expected to add to the explosion P waves at all azi-

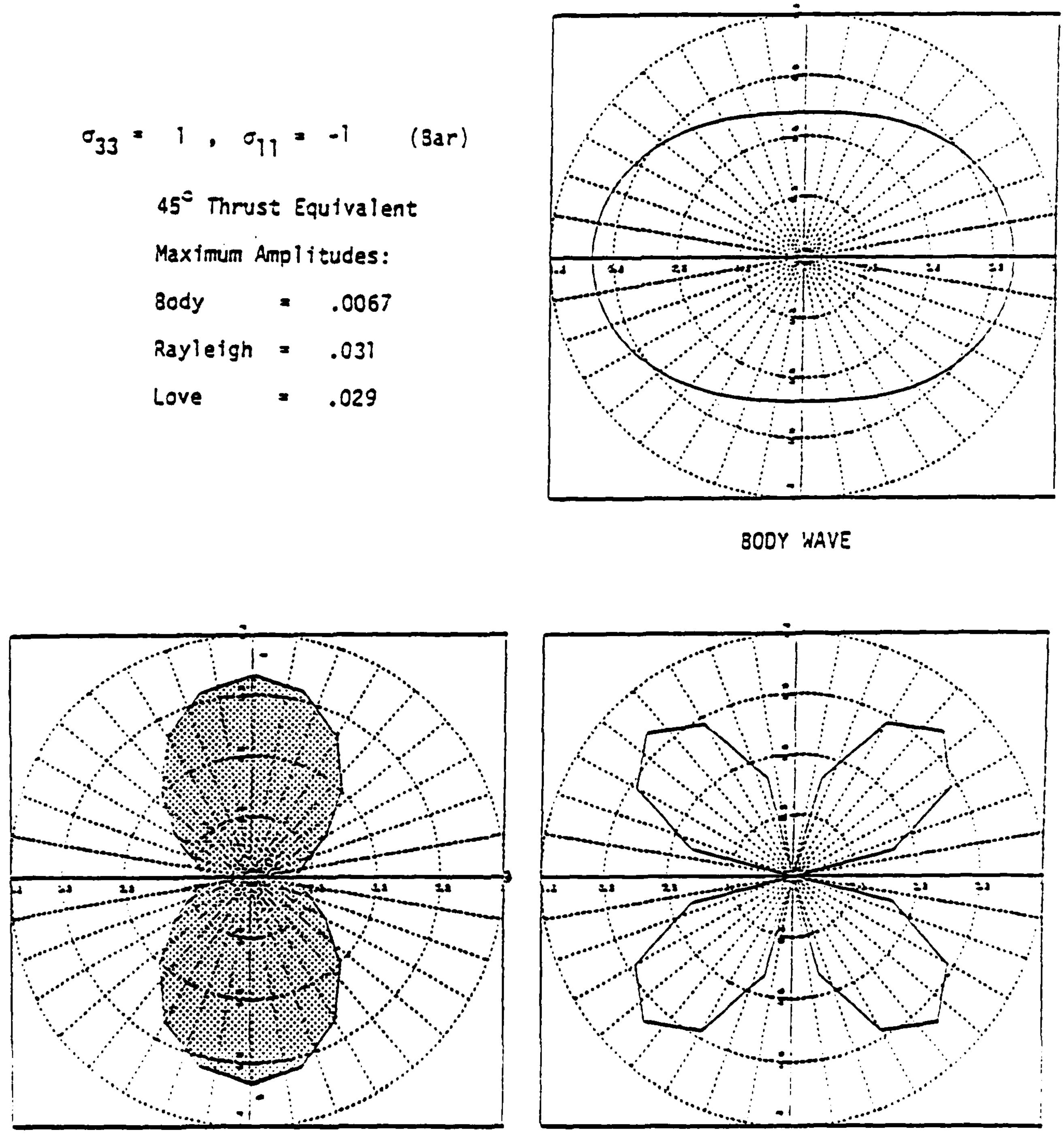

Figure 21. Theoretical radiation patterns for body and surface waves for tectonic release in a uniform prestress field equivalent to 45° thrust faulting. Shaded areas indicate polarity opposite to the explosion. Body waves are calculated at 1 Hz and have a 28° takeoff angle. Surface wave amplitudes are computed at 20 second period. (Stevens, 1982).

muths. Conversely, the tectonic Rayleigh waves tend to cancel the explosion Rayleigh waves at all azimuths, although the radiation pattern is less uniform than that for the body waves. It follows that, in this case, the effects of tectonic release on m_b and M_s can not be eliminated by averaging over the radiation pattern using observations from a well distributed network of stations. Moreover, this focal mechanism is much more efficient at generating teleseismic P waves than the vertical strike-slip mechanism of Figure 20. In this case, a stress drop of only about 150 bars is required to produce tectonic P waves which are as large as the explosion P waves, as opposed to the 30 bar stress drop required to produce tectonic Rayleigh waves as large as those induced by the explosion. Thus, tectonic release corresponding to dip-slip motion on a fault dipping at about 45 degrees has the potential to significantly modify explosion m_b values for physically plausible values of the stress drop. In particular, a focal mechanism corresponding to normal faulting on a plane with this orientation (as opposed to the thrust mechanism illustrated in Figure 21) could lead to a reduction in m_b consistent with that observed for Rulison.

The preliminary observations summarized above provided the motivation for a more specific, quantitative investigation of tectonic release on Rulison. For the purposes of this analysis, the Mueller/Murphy (1971) source description for Rulison has been employed and tectonic release corresponding to normal faulting on a plane dipping at 45 degrees has been modeled. The resulting synthetic explosion teleseismic P wave is shown in Figure 22 where it is compared with the predicted teleseismic tectonic P wave produced by a 1 bar stress drop in a spherical cavity with a radius corresponding to the Mueller/Murphy elastic radius for Rulison.* These synthetics

*These synthetic seismograms were provided by Jeff Stevens of S-CUBED.

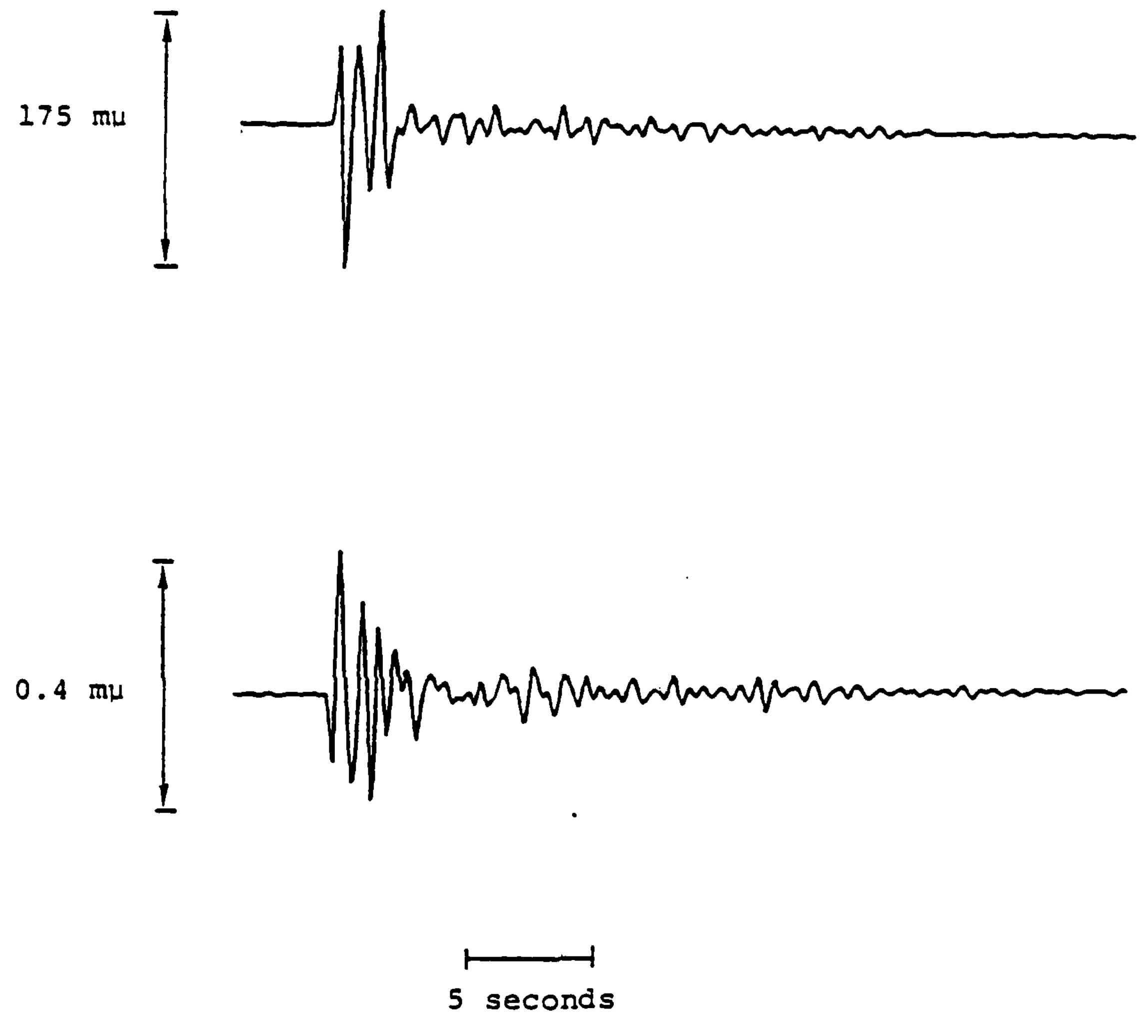

Figure 22. Comparison of theoretical short-period teleseismic P waves for the Rulison explosion (top) and tectonic release corresponding to normal faulting on a plane dipping at 45° (bottom). The synthetic tectonic release P wave amplitude corresponds to a reference level stress drop of 1 bar.

have been computed using the Rulison crustal model of Figure 9 and a t* value of 0.5 seconds. As expected on the basis of Figure 21, the initial P wave induced by this tectonic release is 180 degrees out of phase with the corresponding explosion P wave. In fact, for this case in which the observation point is taken to be at an azimuth of 90 degrees with respect to the strike, the entire first three cycles of the tectonic P waves form a nearly perfect mirror image of the corresponding explosion P waves. It follows that the superposition of the P waves from these two sources would not be expected to give rise to a significantly more complex P wave recording showing obvious evidence of interference effects.

A somewhat surprising result of the calculation illustrated in Figure 22 is that it indicates that a stress drop in excess of 400 bars would be required to cancel the explosion P waves or, perhaps more relevantly, that a stress drop on the order of 200 bars would be required to reduce the composite P wave amplitude by a factor of two (*i.e.*, reduce m_b by 0.3 units). At first glance, this appears to be inconsistent with the results shown in Figure 21 which indicated that, for this assumed focal mechanism, a stress drop of only 150 bars would cancel the explosion P waves. The explanation for this apparent discrepancy can be understood by noting that the example of Figure 21 corresponds to an explosion (Pile Driver) which was detonated at a normal scaled depth of burial of about 120 $m/kt^{1/3}$ while that of Figure 22 corresponds specifically to Rulison, which was detonated at an unusually large scaled depth of burial of 750 $m/kt^{1/3}$. Now the Mueller/Murphy (1971) source scaling model for explosions predicts that the elastic radius decreases with increasing source depth ($r_{el} \sim h^{-1/2}$) and, since the tectonic P wave strength in the Archambeau (1972) tectonic release model is proportional to r_{el}^3, it follows that the stress drop required to produce a teleseismic P wave of a given amplitude

is predicted to increase with increasing explosion source depth. Thus, in order for tectonic release to be considered a credible explanation for the Rulison m_b anomaly, it must be demonstrated that the associated stress drop was on the order of several hundred bars. Although this is large by NTS standards, it should be noted that Rayleigh, *et al.* (1972) in their analysis of the stress regime at a site near Rangely, Colorado, which is located only about 100 km NW of Rulison, inferred horizontal stress differences on the order of 300 bars at depths comparable to the Rulison emplacement depth (*i.e.*, about 2.5 km). Thus, the hypothesis is worthy of more detailed investigation.

In an attempt to obtain a quantitative estimate of the magnitude of the tectonic release on Rulison, a theoretical simulation analysis of selected observed SH pulses, such as that shown in Figure 19, was conducted. These simulations were carried out using the locked-mode, modal synthesis technique developed by Harvey (1981) and applied previously by Murphy, *et al.* (1982) in a simulation analysis of the Gasbuggy near-regional data. In this approach, an artificial high velocity cap layer is added to the bottom of the structure to be modeled so that most of the propagating seismic energy is confined above this boundary, and then the entire seismogram, including body as well as surface wave arrivals, is approximated by a superposition of normal modes. Harvey has shown that this technique can be used to compute accurate, broadband synthetic seismograms for near-regional observation points.

The crustal model selected for the Rulison near-regional SH simulation is shown in Figure 23 where it can be seen that it is essentially a layer over a halfspace. This model represents a simplified version of that shown previously in Figure 9 and has been adapted to improve computational efficiency. The seismic source function corresponding to the

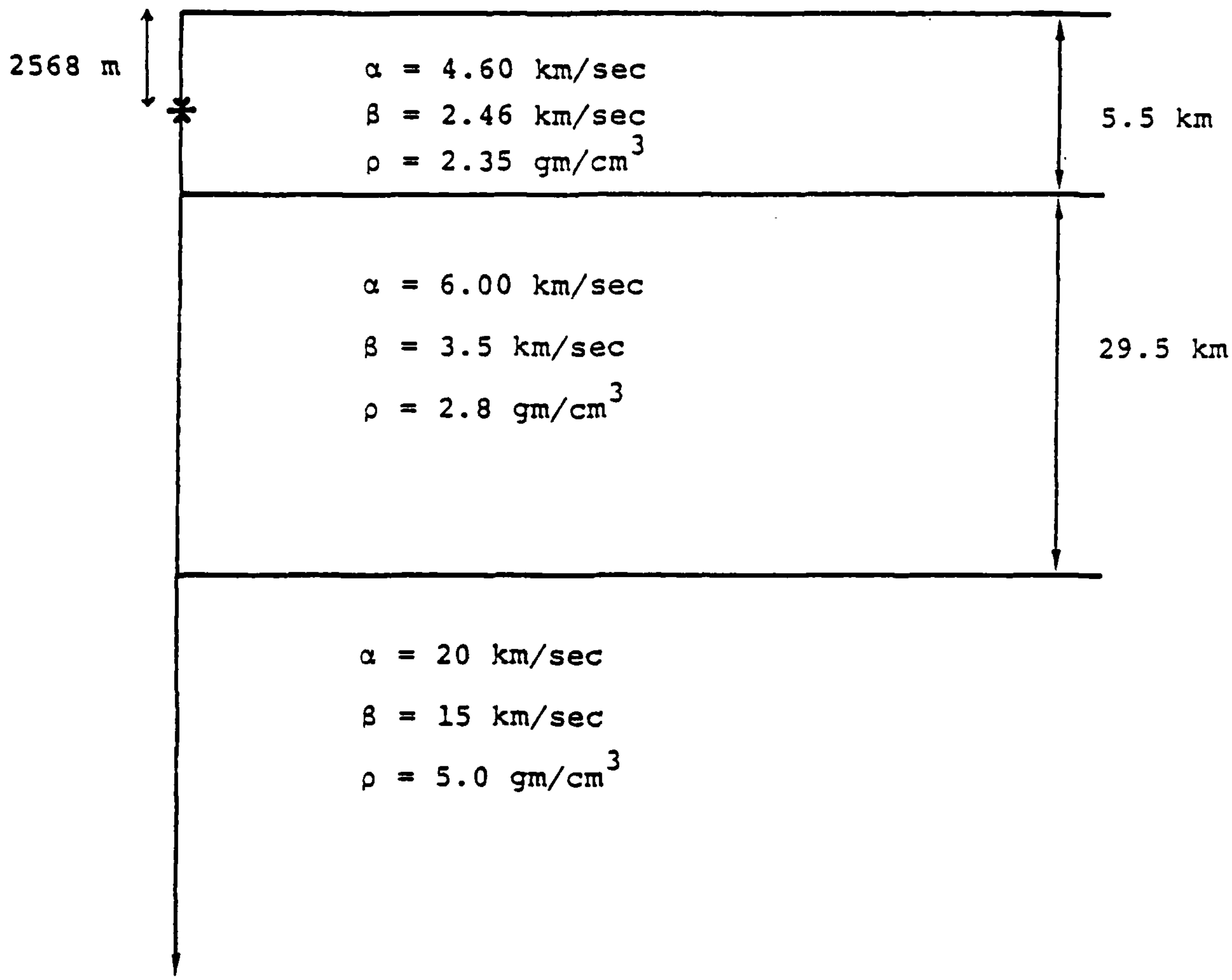

Figure 23. Simplified crustal model for Rulison near-regional tectonic simulation analyses.

general Archambeau tectonic release model is complex (Archambeau, 1972; Stevens, 1980) and has not yet been formally incorporated into Harvey's modal synthesis code. Therefore, for the purposes of this application, the seismic source has been approximated using the following line of reasoning. The tectonic source description currently available in the modal synthesis model is the traditional point double couple with a source time function defined by a time dependent seismic moment, $M_o(t)$. The orientation of this double couple has been chosen to correspond to the uniform prestress which maximizes the destructive interference effect on the explosion teleseismic P waves and thus corresponds to a fault plane dip of 45 degrees and a rake of -90 degrees (*i.e.*, normal faulting). The time dependence of the source has been selected to match the time dependence of the far-field displacement pulse predicted by the Archambeau model. That is, since the far-field displacement, U(t), is proportional to the time derivative of the seismic moment, $\dot{M}_o(t)$, $\dot{M}_o(t)$ is specified to agree with the far-field shear wave time dependence predicted by the Archambeau model. Now the frequency dependence of the far-field shear wave spectrum for this model of tectonic release can be approximated by the expression (Archambeau, 1972)

$$F(\omega) = \frac{1}{k_\beta^2}\left[\cos k_\beta R_0 - \frac{\sin k_\beta R_0}{k_\beta R_0}\right]$$

where $k_\beta = \omega/\beta$ and $R_0 = r_{el}$. For Rulison, $\beta \approx 2.46$ km/sec and $r_{el} \approx 260$ m, giving the far-field displacement spectral shape shown as the solid line in Figure 24. It can be seen that this spectrum is flat at low frequency and rolls off asymptotically as ω^{-2} above a corner frequency of about 2.5 Hz. In fact, the principal features of this far-field S wave displacement spectrum are very similar to those of a second order lowpass filter with the same corner frequency, as is

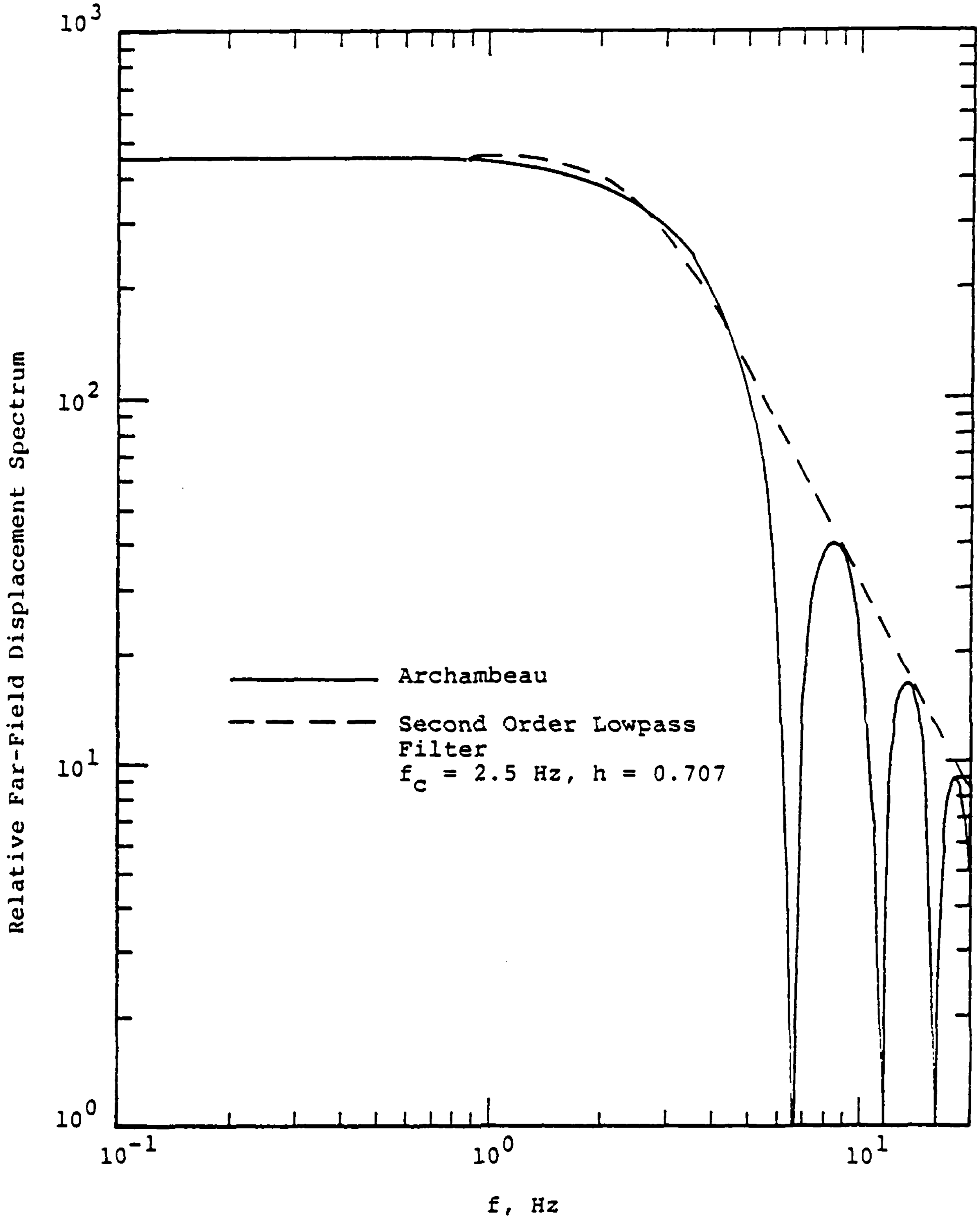

Figure 24. Comparison of Archambeau and lowpass filter approximations to the Rulison tectonic release far-field S wave spectrum.

indicated by the dashed line on Figure 24. Consequently, because of its analytical simplicity, the lowpass filter response has been taken to approximate the far-field displacement spectrum. The transfer function of a second order lowpass filter can be written in the form

$$H(\omega) = \frac{\omega_0^2}{(\omega_0^2 - \omega^2) + i\ 2h\omega_0\ \omega}$$

where $\omega_0 = 2\pi f_c$, f_c is the corner frequency and h is the percentage of critical damping, taken here as 0.707. Thus, taking the inverse transform of $H(\omega)$, $\dot{M}_0(t)$ has the form

$$\dot{M}_0(t) = h(t) = \frac{\omega_0 e^{-h\omega_0 t}}{\sqrt{1-h^2}} \sin \omega_0 \sqrt{1-h^2}\, t$$

The interest in the present simulation analysis is in particle velocity waveforms which, in the far-field, will be proportional to $\ddot{M}_0(t)$, given by

$$\ddot{M}_0(t) = \dot{h}(t) = \frac{\omega_0 e^{-h\omega_0 t}}{\sqrt{1-h^2}} \left[\omega_0 \sqrt{1-h^2} \cos \omega_0 \sqrt{1-h^2}\, t - h\omega_0 \sin \omega_0 \sqrt{1-h^2}\, t \right]$$

The time dependence represented by this function, as seen through a 0 to 10 Hz passband, is shown in Figure 25.

With this definition of the source and propagation path, synthetic SH seismograms corresponding to a frequency band extending from 0.01 to 10 Hz have been computed for observation points corresponding to several near-regional locations at which a significant SH pulse was recorded from Ruli-

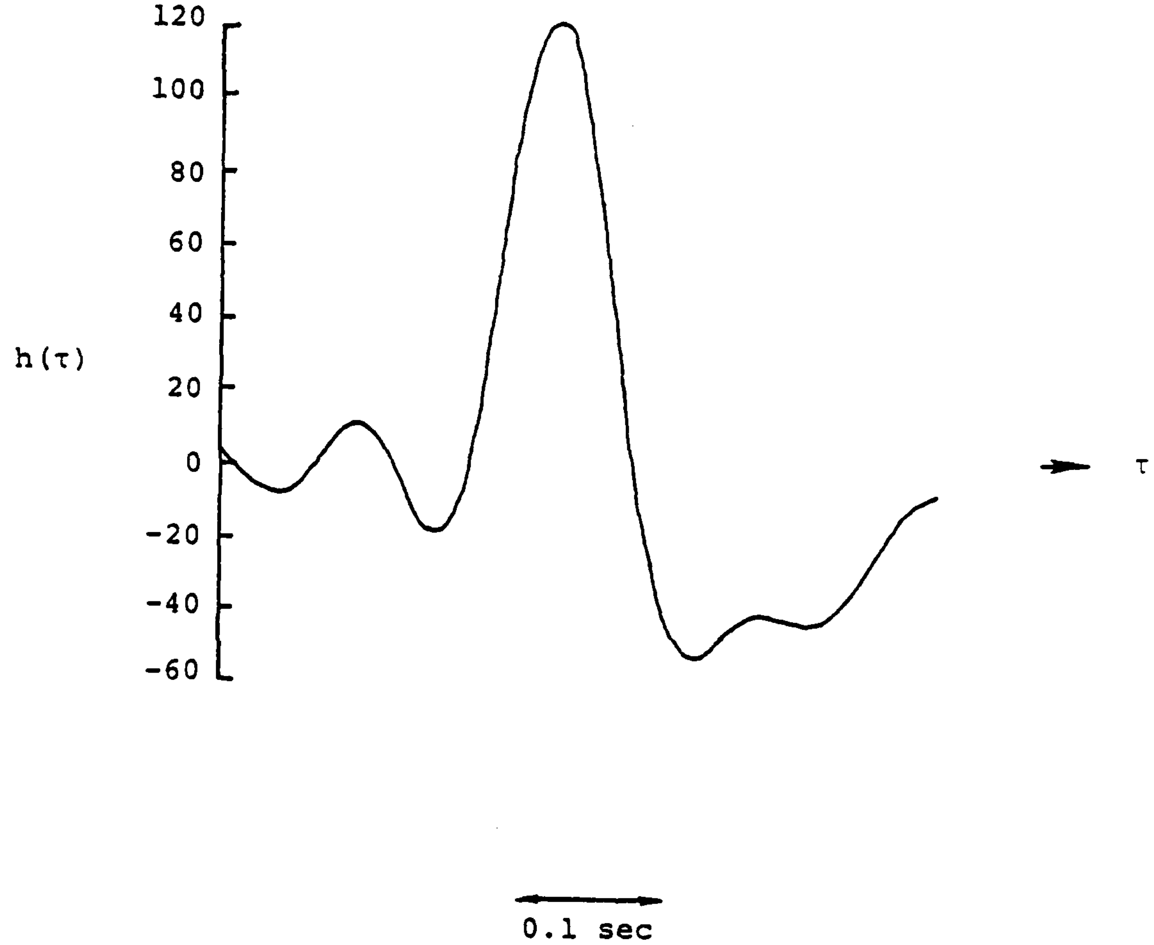

Figure 25. Far-field S wave velocity pulse corresponding to the lowpass filter analytical approximation as seen through the 0 to 10 Hz passband.

son. Computed and observed transverse-component particle velocity seismograms at a distance of 23 km are compared in Figure 26. It can be seen that the synthetic seismogram, which corresponds to an azimuth which is a maximum on the SH wave radiation pattern, is very simple and is dominated by a relatively few discrete arrivals with waveforms quite similar to the analytically derived, far-field SH velocity pulse of Figure 25. Note that, despite the oversimplified nature of the propagation path model of Figure 23, the main feature of the observed SH arrivals are reasonably well reproduced by the synthetic, and thus the synthetic results can provide a basis for a quantitative estimate of the stress drop associated with the tectonic release on Rulison. In particular, the dominant frequency of the synthetic SH arrivals agrees with that of the observed, and this suggests that the selected corner frequency shown in Figure 24 is approximately correct. The seismic moment, M_o, corresponding to the synthetic seismogram shown in Figure 26 is $2\pi \times 10^{21}$ dyne-cm and this gives rise to a peak velocity of 0.6 cm/sec as opposed to the observed peak value of 4.39 cm/sec at this range. It follows that the moment required to reproduce the observed peak velocity is

$$M_o = \frac{4.39}{0.6} \times 2\pi \times 10^{21} = 4.6 \times 10^{22} \text{ dyne-cm}$$

Now for Archambeau's tectonic release model, the relation between stress drop, σ, and moment M_o is given by (Stevens, 1982)

$$\sigma = \frac{M_o}{\left[\dfrac{20\pi\ \alpha^2}{9\alpha^2 - 4\beta^2}\right] R_o^3}$$

It follows from this relation that with $\alpha = 4.6$ km/sec, $\beta = 2.46$ km/sec, $R_o = 2.6 \times 10^4$ cm and $M_o = 4.6 \times 10^{22}$ dyne-cm,

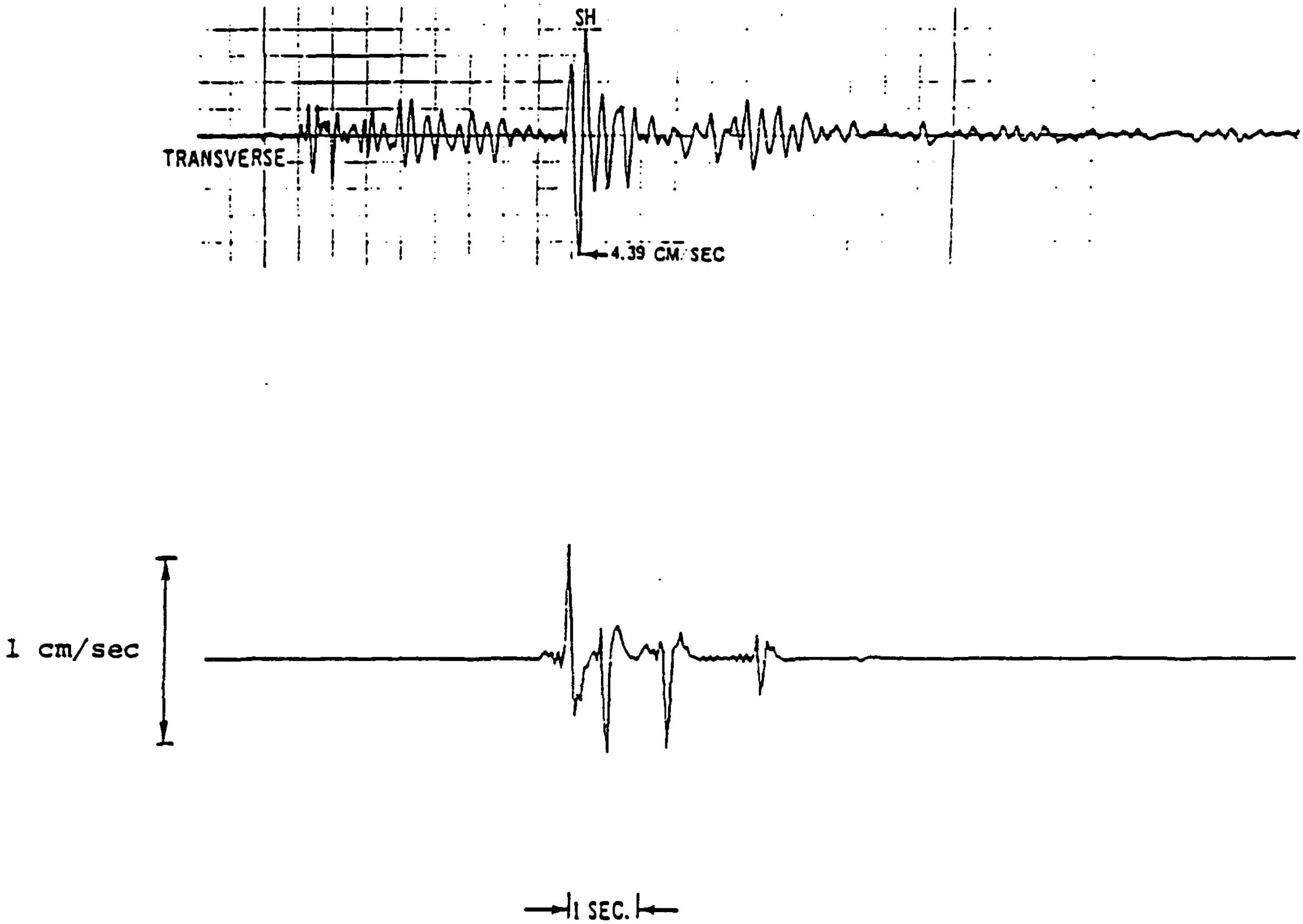

Figure 26. Comparison of observed (top) and theoretical (bottom) transverse particle velocity seismograms for Rulison, Δ = 23 km.

the inferred stress drop is

$$\sigma = 3.2 \times 10^8 \text{ dynes/cm}^2 = 320 \text{ bars}$$

A similar analysis of the SH pulse observed from Rulison at a range of 9 km gives a stress drop estimate of 250 bars. Thus, the observed near-field SH waves from Rulison are consistent with a 250-300 bar stress drop for an assumed homogeneous prestress field consistent with normal faulting on a plane dipping at 45 degrees. With reference to Figure 22, such a tectonic release could be expected to suppress the teleseismic m_b value for Rulison by more than 0.3 units m_b. Thus, the inferred tectonic release on Rulison can explain the observed m_b/yield anomaly.

The above results provide strong evidence supporting the hypothesis that tectonic release on Rulison may explain the Rulison/Gasbuggy m_b anomaly. However, this explanation raises some additional questions regarding the interpretation of the observed Rulison data. For example, direct comparisons of the near-regional data observed from Gasbuggy and Rulison have been used to argue that the explosion source coupling of Rulison was not anomalous (Murphy, *et al.*, 1982). It is, therefore, reasonable to inquire to what extent the inferred tectonic release on Rulison might have affected these comparisons. In order to address this issue, synthetic P/SV seismograms corresponding to the explosion and the tectonic release inferred above have been computed using Harvey's modal synthesis technique with the simplified propagation path model of Figure 23. The synthetic explosion and tectonic radial-component particle velocity seismograms (0.01 to 10 Hz passband) computed at a range of 25 km are compared with each other and with their linear superposition in Figure 27. For this comparison, the tectonic release component has been evaluated at an azimuth of 30 degrees from the strike, which

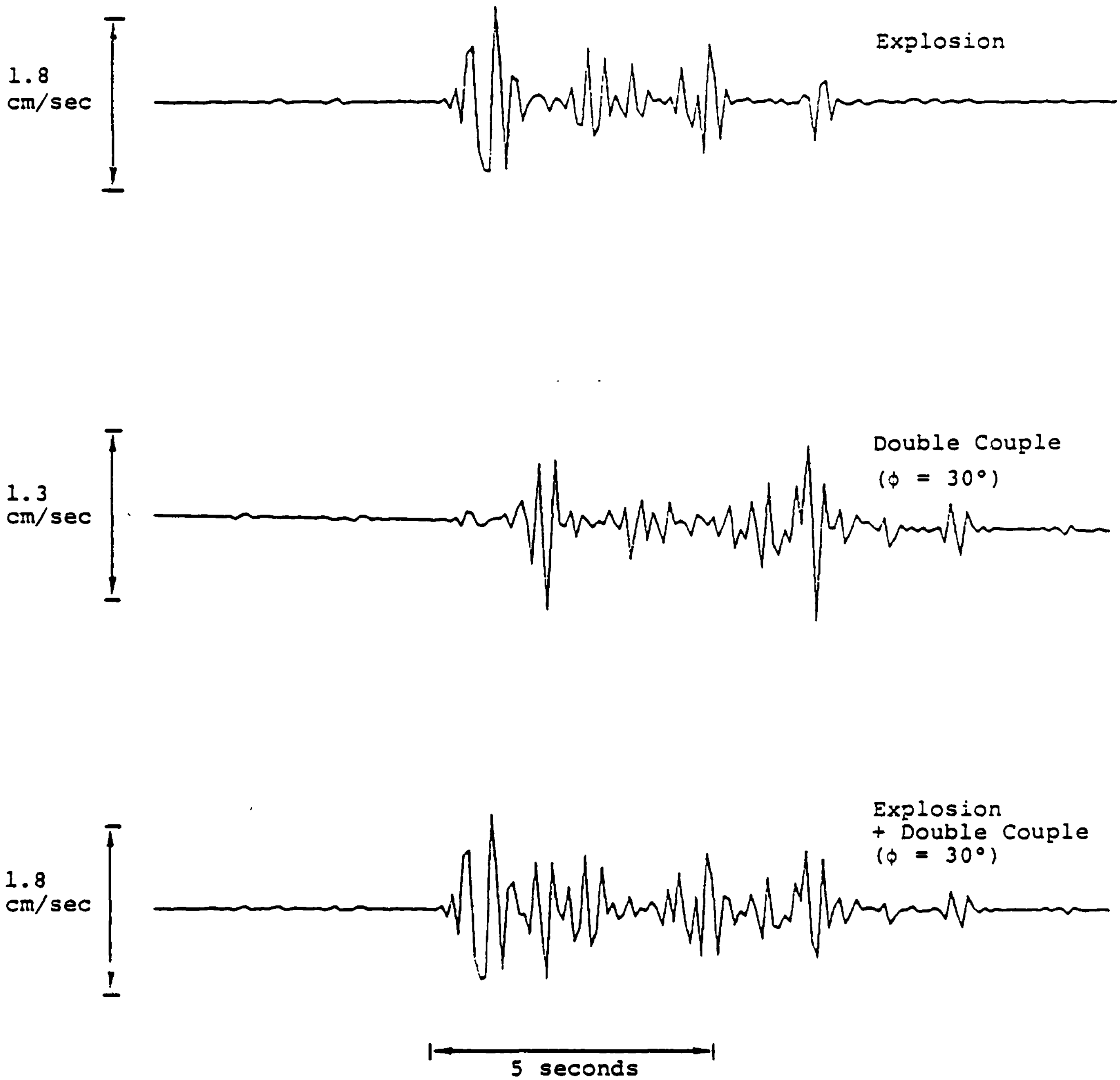

Figure 27. Comparison of theoretical radial component particle velocity seismograms computed for the Rulison explosion and tectonic release, R = 25 km.

is an intermediate point on the SV radiation pattern. It can be seen that, although the superposed waveform is more complex than that due to the explosion alone, the amplitude level is not significantly affected and the explosion waveform appears to dominate the composite. Thus, although this question deserves more detailed investigation, these preliminary results suggest that the proposed tectonic release may not seriously compromise the near-regional comparisons such as those shown in Figure 3.

Finally, it is appropriate to consider whether the observed long-period surface waves, which have traditionally been used to study tectonic release effects, are consistent with the proposed tectonic release model for Rulison. Figure 28 shows the observed M_s values for Gasbuggy, Rulison and Rio Blanco, compared with a least-squares M_s/yield relation obtained using a sample of NTS explosions in wet tuff (Marshall, *et al.*, 1979). It is interesting to note that these M_s values show no pronounced anomaly comparable to the m_b anomaly of Figure 2 and provide additional evidence which suggests that it is indeed the Rulison and Rio Blanco m_b values which are anomalous. In any case, it is clear that, whatever the source of the anomaly is, it has less effect on M_s than on m_b. In fact, it can be shown that, using the Rulison tectonic release model inferred above and assuming a well distributed network of stations to average over the Rayleigh wave radiation pattern of Figure 21, it would be expected that the observed M_s value would be inflated by less than 0.2 units, which is not inconsistent with the data shown in Figure 28. Thus, the proposed Rulison tectonic release model appears to be compatible with the observed M_s value. A comprehensive analysis of the long-period Love waves recorded from this event would almost certainly provide a more definitive answer to this question. However, the signal-to-noise characteristics of most of the horizontal component, long-period surface waves

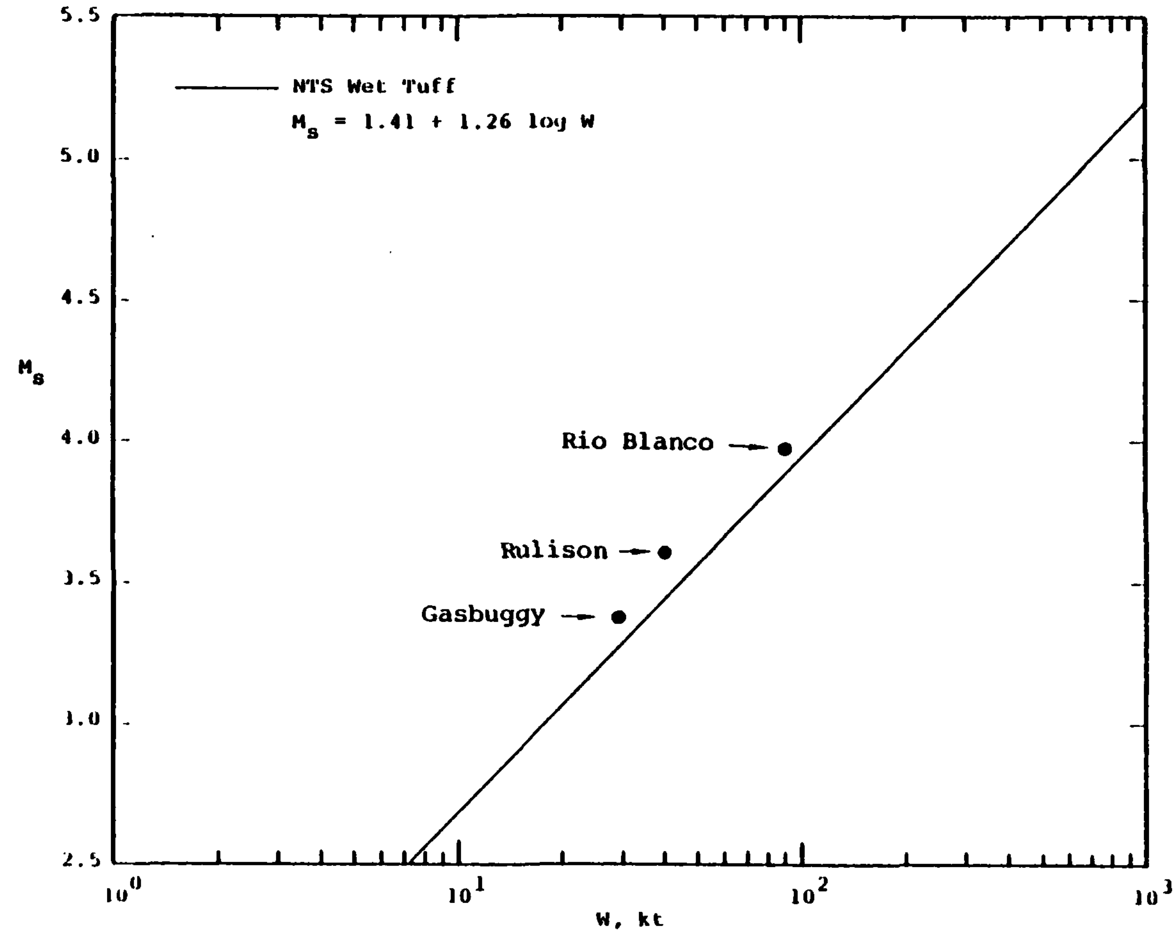

Figure 28. Comparison of M_S/yield values for Gasbuggy, Rulison and Rio Blanco with average NTS wet tuff M_S/yield relation.

recorded from this relatively small event are poor and, consequently, it will probably be necessary to initiate a supplemental study to digitize and prefilter these data if reliable results are to be obtained.

IV. SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The research investigations summarized in this report have centered on an attempt to develop a quantitative understanding of the Rulison/Gasbuggy m_b/yield anomaly and to assess its implications with regard to the definition of magnitude/yield variability in the Western United States. This effort has encompassed comparative studies of near-regional, regional and teleseismic data recorded from these two explosions, as well as theoretical simulation analyses of selected near-regional and teleseismic data sets. Various hypotheses which have been proposed to explain the m_b anomaly, including differences in explosive source coupling, variations in upper mantle attenuation beneath the two test sites and tectonic release effects, have been considered and critically evaluated in terms of their consistency with respect to the various seismic data sets which were recorded from these events.

An overview of the characteristics of the Rulison/Gasbuggy m_b/yield anomaly was presented in Section I, with particular emphasis on the interpretation of the evidence provided by the recorded near-regional seismic data. In particular, it was demonstrated that the observed Rulison broadband, near-regional data agree very well with the results obtained by scaling average Gasbuggy observations using the Mueller/Murphy source scaling model. A theoretical simulation of the observed Gasbuggy near-regional data was also described and used, in conjunction with the scaling results, to conclude that the observed m_b/yield anomaly can not be attributed to differences in explosive source coupling between the two test sites.

Teleseismic P wave data recorded from Gasbuggy and Rulison at common WWSSN stations were compared and analyzed in Section II. Theoretical simulation analyses of these data

were presented and it was demonstrated that if the observed differences in the P wave amplitudes recorded from these events are to be attributed to variations in upper mantle attenuation between the two test sites, then the t* values characteristic of their teleseismic propagation paths must differ by 0.3 to 0.4 seconds. A variety of P wave spectral data from the two events were then compared and found to be inconsistent with such large differences in t*. In fact, it was demonstrated that the available spectral data are best described under the assumption that the attenuation bias between the Gasbuggy and Rulison sites is effectively zero.

An alternate hypothesis, that the observed m_b/yield anomaly may be due to tectonic release effects on Rulison, is examined in Section III. Examples were presented which confirm that long-period Love waves as well as unusually strong and coherent near-regional SH arrivals were observed from Rulison, providing evidence that significant tectonic release did, in fact, occur on this event. This presentation was followed by a discussion of the influence of tectonic release on teleseismic P waves in which it was shown that, although such effects are generally not expected from release equivalent to vertical strike-slip faulting, tectonic release corresponding to dip-slip motion on a fault dipping at about 45 degrees has the potential to significantly modify explosion m_b values for physically plausible values of the stress drop. On the basis of this observation, a theoretical simulation analysis of the observed Rulison near-field SH pulse was performed and used to infer the magnitude of the tectonic release which produced it. It was then demonstrated that this inferred tectonic release can quantitatively explain the observed m_b/yield anomaly on Rulison.

4.2 CONCLUSIONS

The analyses described above support the following conclusions concerning the Rulison/Gasbuggy m_b/yield anomaly.

1. The evidence provided by the near-regional, broadband seismic data recorded from these two explosions indicates that the m_b/yield anomaly is not due to differences in explosive source coupling. That is, the frequency dependent differences in these observed ground motions are consistent with those predicted by the Mueller/Murphy approximate source model.

2. Comparisons of P wave data recorded from Gasbuggy and Rulison at common teleseismic WWSSN stations indicate that the m_b anomaly is consistently observed at a variety of distances and azimuths.

3. The Gasbuggy teleseismic P wave data are characterized by a strong secondary arrival which can not be accounted for by theoretical simulations employing a simple, spherically symmetric source model. It has been demonstrated that the characteristics of this secondary arrival are consistent with the observed surface spallation on Gasbuggy.

4. The observed differences in the relative spectral composition of the P waves recorded from Gasbuggy and Rulison, at the WWSSN station at College, Alaska and at three different LRSM stations, are not consistent with the hypothesis that the m_b/yield anomaly is due to differences in upper mantle attenuation beneath the two test sites. That is, these data are consistent

with the "reciprocal" data of Der, *et al.* (1981) and provide strong evidence that no large attenuation bias exists between these two test sites.

5. Significant tectonic release occurred on Rulison. This is confirmed by the observations of long-period Love waves as well as unusually strong and coherent near-regional SH arrivals from this event.

6. The observed Rulison/Gasbuggy m_b/yield anomaly can be quantitatively explained by the inferred tectonic release on Rulison. The observed SH waves from Rulison can be theoretically simulated using a model in which a 250-300 bar stress drop occurs in a homogeneous prestress field consistent with normal faulting on a plane dipping at 45 degrees. Such a tectonic release would be expected to decrease the associated explosion m_b value by more than 0.3 units.

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